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Atlantic Application of the Systematic Approach to Tropical Cyclone Track Forecasting: Part I. Environmental Structure Characteristics

by

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13. ABSTRACT (Maximum 200 words.)
This Meteorological knowledge base for application of the Systematic Approach to Tropical Cyclone Track Forecasting in the Atlantic basin follows from similar knowledge bases previously developed for the western North Pacific, the eastern and central North Pacific, and the Southern Hemisphere. A common environment structure terminology has been adopted in which three synoptic patterns (Standard, Poleward, and Midlatitude) are found in each of these basins. Each basin also has a special pattern, which in the Atlantic is the Upper-level low. The conceptual models for these synoptic patterns with their associated synoptic regions are described here via a conceptual model, analysis examples, and the characteristic track segments within each region. A climatology of occurrences in each patter/region for the 1568 cases during 1990-98 is prepared. The second key element in the knowledge base is the transitional mechanisms that change the environment structure and thus change the tropical cyclone steering flow. Conceptual models for these mechanisms are presented and illustrated with sequences of analyses. A climatology of recurring (at least four occurrences in nine years) transitions is prepared to indicate the most common track changes during these transitions.

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1. INTRODUCTION

a. *Systematic Approach framework*

The basic concepts of a Systematic and Integrated Approach to Tropical Cyclone (TC) Track Forecasting (hereafter the Systematic Approach) were introduced by Carr and Elsberry (1994) for the western North Pacific region. The central thesis of the Systematic Approach is that the forecaster can formulate track forecasts that improve on the accuracy and/ or consistency of the dynamical or other objective guidance if he/she is equipped with: (*i*) a meteorological knowledge base of dynamically sound conceptual models that classify various TC-environment situations: (*ii*) a knowledge base of recurring TC track forecast errors attributed to various combinations of TC structure and environment structure, and the anticipated changes; and (*iii*) an implementing methodology or strategy for applying these two knowledge bases to particular TC forecast situations.

The basic components of the meteorological knowledge base in the Systematic Approach is given in Fig. 1. Environment structure (Fig. 1, upper left) is defined in terms of synoptic patterns and synoptic regions. Synoptic patterns are classifications of the large-scale environment based on the existence and orientation of circulations such as cyclones and anticyclones. Synoptic regions are smaller regions within the synoptic patterns where certain characteristic directions of environmental steering of the TC may be expected. The TC structure (Fig. 1, upper right) is described in terms of traditional intensity categories and distinguishing between midget, small, average, and large sizes. The motivation for the size grouping, and proposed strategy for determining operationally the size, is given by Carr and Elsberry (1997).

A key element of the Systematic Approach is to recognize transitional mechanisms, which are the environment effects (Fig. 1, lower left) and the TC-environment transformations (Fig. 1, lower right), that will lead to a transition in the environment structure. The fundamental difference between the two types of transitional mechanisms is that the TC plays an active role in the TC-environment transformations, but an essentially passive role (i.e., responding to changing steering) in response to the environmental effects. Because each such synoptic pattern/region transition is associated with a TC track change, it is important that the forecaster be equipped to recognize that a transition is (or will be) occurring. Equipping forecasters to recognize these changes in environment structure is a major goal of the Systematic Approach.

Carr *et al.* (1995) prepared a climatology of 12-h TC and environment structure characterizations for all TCs in the western North Pacific during 1989-1993, and this lead to a refinement of the Systematic Approach. This climatology has subsequently been extended through the 1997 TC season for the western North Pacific. A similar climatology of the environmental structure has been prepared in the eastern and central North Pacific (White 1995, Boothe 1997, Boothe *et al.* 1997). A preliminary climatology was also prepared for the Atlantic (Kent 1995). Bannister *et al.* (1997, 1998) examined the possible adaptation of the Systematic Approach meteorological knowledge base to all Southern Hemisphere TCs during the 1990-91 through 1997-98 seasons. Reader *et al.* (1999) added the 1998-1999 season.

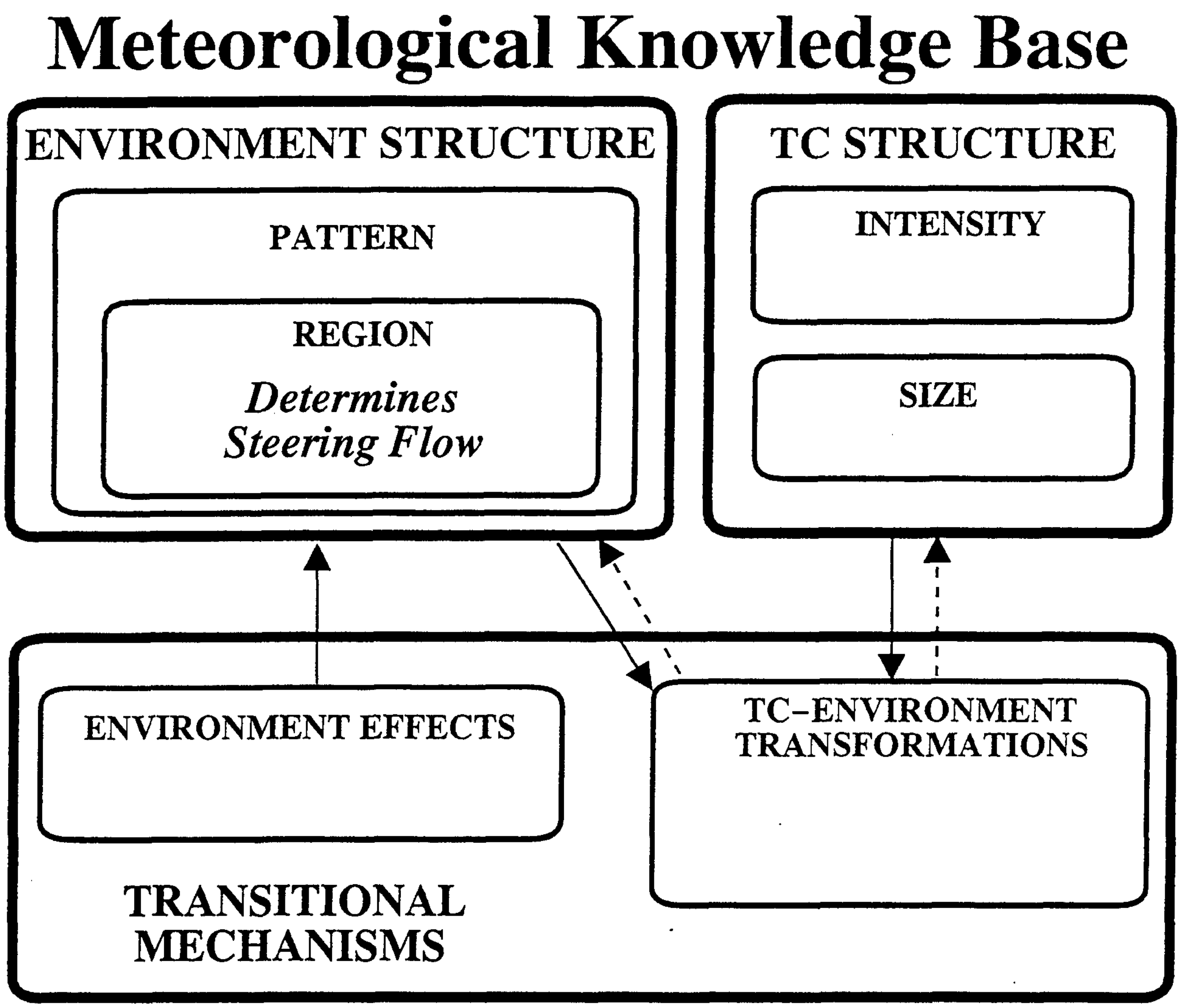


Fig. 1. General framework of the Meteorological knowledge base of the Systematic Approach with the Environment structure and the TC structure that describe the present situation and the transitional mechanisms of environment effects and TC-environment transformations that are operating to change the track.

Although the synoptic patterns and synoptic regions that make up the environment structure vary slightly in the TC basins examined thus far, the important conclusion is that all TC scenarios have been able to be classified with only a small set of conceptual models. Furthermore, the basic Systematic Approach concepts of associating characteristic TC tracks with specific synoptic environment circulations, and identifying TC structure characteristics that may lead to an environment structure change, have been demonstrated to be valid. Making allowance that the specific transformation mechanisms do vary among the TC basins examined thus far, a (retrospective) explanation for all significant track changes has been possible in terms of only a small set of transitional mechanisms.

The Joint Typhoon Warning Center (JTWC), Hawaii, forecasters have utilized the environment structure aspect of the Systematic Approach for several seasons. The second knowledge base of recurring track forecast errors by dynamical models has recently been developed for western North Pacific TCs (Carr and Elsberry 1999), and versions have been introduced to JTWC forecasters. The third aspect of an implementing methodology progressed during the second half of the 1999 season with a successful beta-test of the Systematic Approach Forecasting Aid (SAFA), which is a knowledge-based expert system (Carr *et al.* 2000).

b. Objectives

The primary objective of this study has been to examine the possible adaptation of the Systematic Approach meteorological knowledge base to Atlantic TCs. This is more than just adding four more years to the data base of Kent (1995), because new understandings have been gained in the applications of the Systematic Approach to the eastern/central North Pacific (Boothe 1997) and to the Southern Hemisphere (Bannister *et al.* 1997, 1998, Reader *et al.* 1999). Detailed examination of the larger Atlantic sample has also added new insights, and had led to new terminology that is believed to have global applicability. With this Atlantic application of the Systematic Approach, only the North Indian Ocean TCs will not have been examined.

This report describes the meteorological knowledge base in Fig. 2 that is specifically for the Atlantic. This report has the following four specific objectives.

(*i*) Examination of a large number of Atlantic cases has led to three conceptual synoptic patterns that are common to other basins, and one pattern that is specific to the Atlantic environment (Fig. 3). The goal is to identify synoptic patterns and synoptic regions that the Atlantic forecaster can use to develop a "storyline" that explains the present and recent past TC motion, i.e., a physically based environment structure description of the circulations that are determining the present track. In future work, it will be demonstrated that it is the ***improper representation*** of these circulations in the numerical models that leads to large track forecast errors. Thus, it is important to identify these circulations in the model initial conditions to continue consistently the storyline into the forecast period.

(*ii*) A "climatology" of synoptic patterns and regions that summarizes the frequency of occurrence, and the characteristic track segments associated with each synoptic pattern/region combination will be presented.

(*iii*) Specific physical mechanisms have been identified that lead to changes in the TC track, and conceptual models have been identified that describe the environment structure changes leading to the track changes. Case studies that illustrate the sequence of environment structure changes in operational analyses will be presented.

(iv) A "climatology" of environment structure changes has been prepared as a basis for assessing how often specific transitions from one synoptic pattern/region combination to another combination occur. Given knowledge of the synoptic pattern/region, only certain transitions to other pattern/region combinations have been observed. It is useful background for the forecaster to know how common or how rare an anticipated synoptic pattern/region transition (and thus an associated track change) is.

Meteorological Knowledge Base for the Atlantic

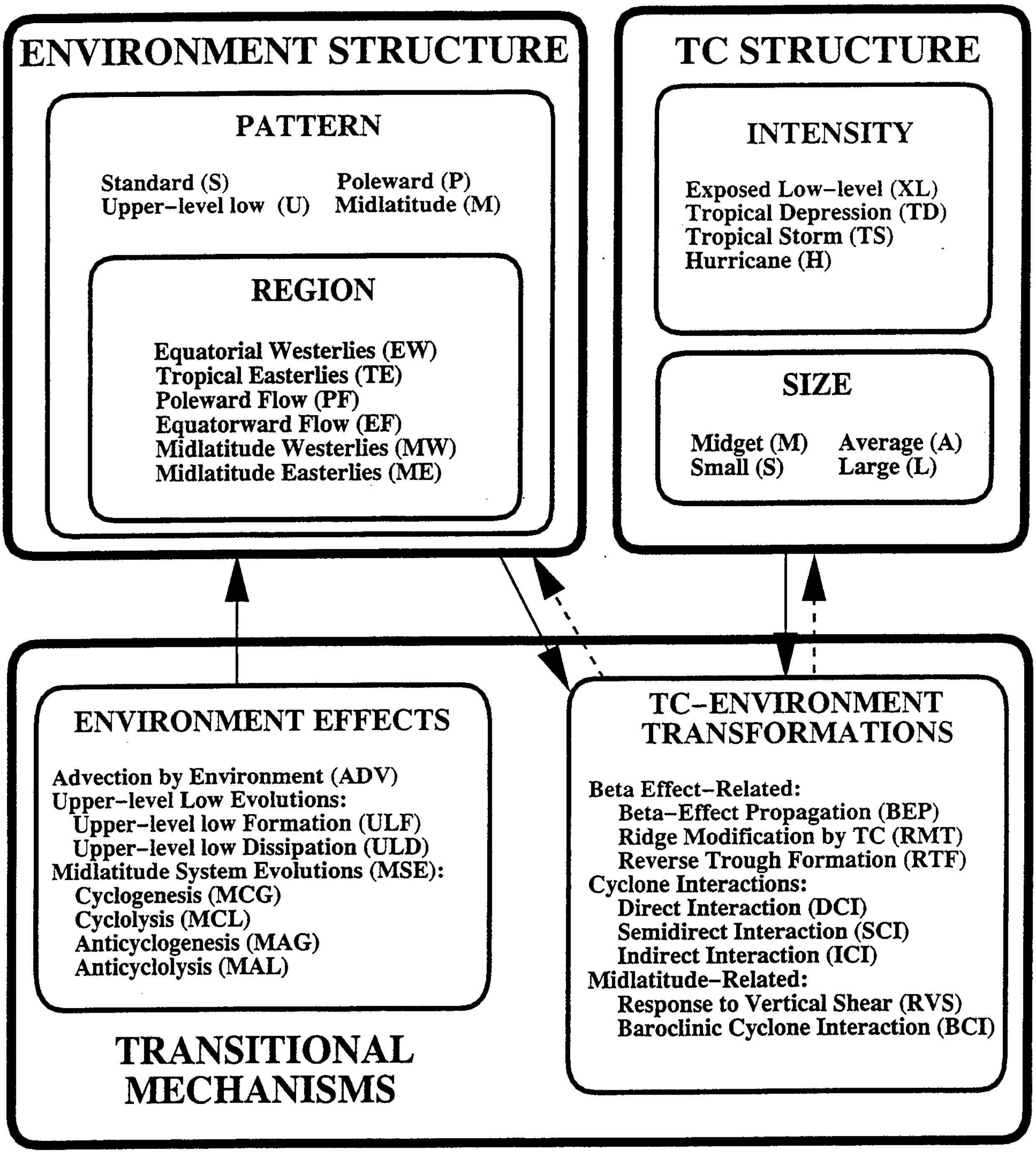


Fig. 2. Meteorological knowledge base as in Fig. 1, except specifically for application of the Systematic Approach to the Atlantic TCs.

ATLANTIC
SYNOPTIC PATTERNS AND REGIONS

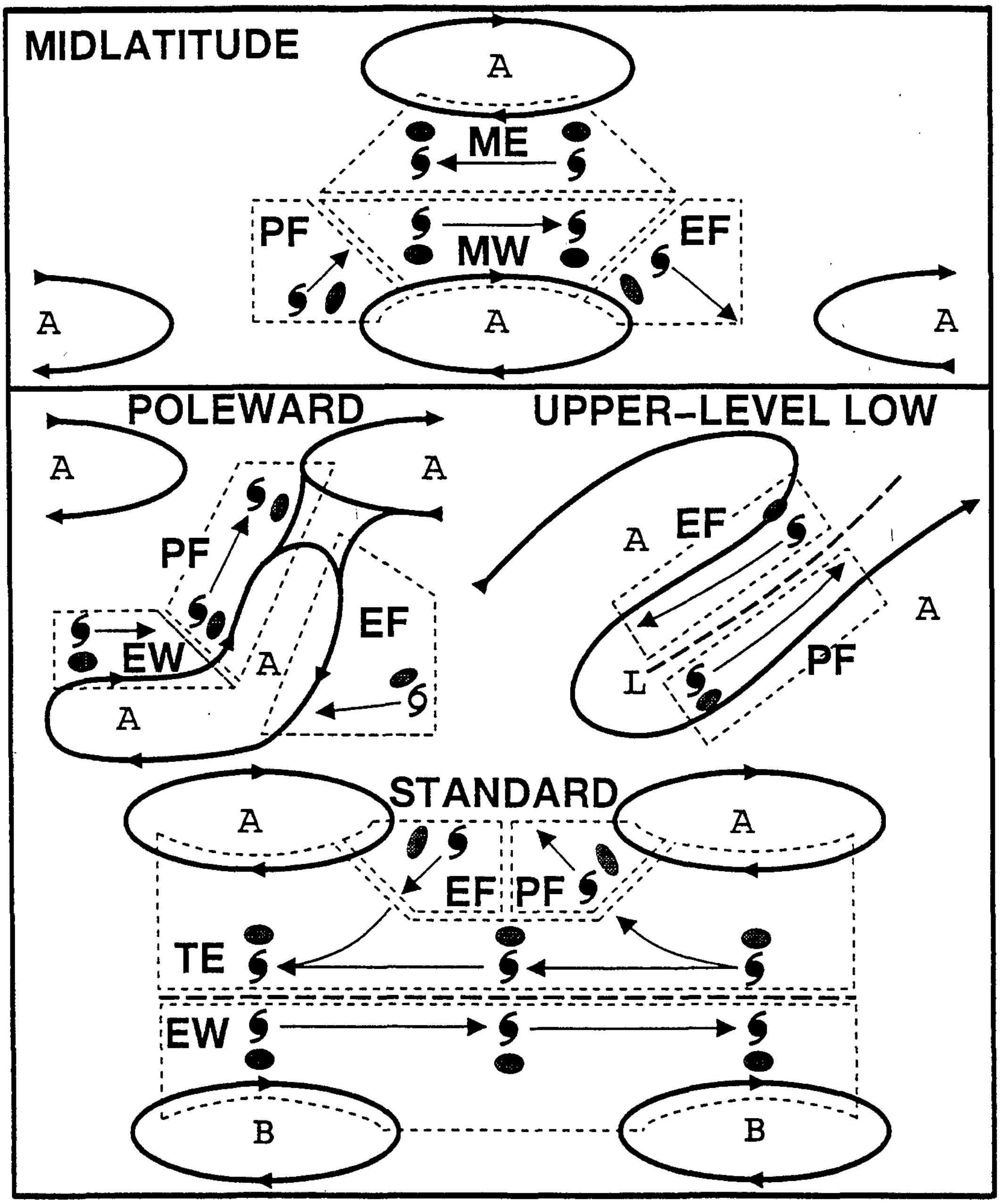


Fig. 3. Environment structure conceptual models in the Meteorological knowledge base for the Atlantic (Fig. 2, upper left) in terms of four synoptic patterns (Midlatitude, Poleward, Upper, and Standard) and six synoptic regions (light dashed lines, see meaning of acronyms in Fig. 2). Whereas the three synoptic patterns in the lower panel generally apply while the TC is equatorward of the subtropical anticyclone axis, the Midlatitude pattern in the upper panel applies whenever the TC is poleward of the subtropical anticyclone axis. Thick solid streamlines represent the 500-mb environmental flow after removal of the TC circulation. The heavy dashed line in the lower portion represents the monsoon trough. Light solid arrows illustrate characteristic TC tracks. Isotach maxima relative to the TC positions are indicated by elliptical regions. These schematics depict the steering flow of TCs in terms of Anticyclones (A), an Upper-tropospheric Low (L), and an equatorial Buffer (B) cell.

This report addresses only the first of the three premises in the first paragraph of section 1.a, i.e., the Meteorological knowledge base. Brown (2000) has begun to establish a knowledge base of recurring TC track forecast errors. The implementing methodology or strategy for applying these two knowledge bases to make improved forecasts will eventually take the form of the western North Pacific SAFA adapted for the Atlantic. However, it is expected that this Meteorological knowledge base can assist the forecaster in the essential first step in forecasting, which is to do a careful analysis of the synoptic situation for the purpose of understanding what circulations and physical mechanisms are determining the present TC track.

2. APPROACH

The Systematic Approach environment structure conceptual models have been developed based on the U. S. Navy Operational Global Atmospheric Prediction System (NOGAPS) analyses from the Fleet Numerical Meteorology and Oceanography Center (FNMOC), Monterey, California. Beginning in June 1990, synthetic observations have been included in the NOGAPS analyses to improve the TC location and structure representation. These synthetic observations for Atlantic TCs have been based on the National Hurricane Center (NHC) warning messages. Since October 1994, the synthetic observations have included an adjustment to make the average flow in the region of the TC agree with the recent 12-h motion of the storm as contained in the NHC warnings. The synthetic observations, any rawinsondes or other observations, and a 6-h NOGAPS forecast are blended in the data assimilation system to provide the initial conditions for the global model forecast. Although the 500-mb analyses are typically used to characterize the synoptic pattern/region that determines the steering flow, analyses at 700 mb or lower may be used when the TC is weak or vertical wind shear has affected the upper-tropospheric structure. An archive of NOGAPS analyses and forecasts each 12 h is maintained at the Naval Postgraduate School.

The NHC post-storm (best-track) positions have been used to describe the track and track changes in this Atlantic study. The NHC also kindly provided selected GOES images that were missing from the NPS archives.

As indicated in section 1b, the objective is to classify the environment structure (synoptic pattern/region) in each TC situation using the 12-h NOGAPS analysis and the present and recent motion. The environment structure classifications have been assigned based on the conceptual models of the synoptic pattern/regions developed for the other basins to which the Systematic Approach has been previously applied. It is emphasized that the schematics in Fig. 3 should be regarded as flexible templates. That is, the subtropical anticyclone in the Atlantic may assume a zonal appearance similar to the schematic, or it may be broad and weak, or it may have a more triangular shape. The new Midlatitude and Upper-level low synoptic patterns in Fig. 3 have been developed to account for the variety of midlatitude circulations that exist in the North Atlantic that may affect the motion of TCs. In addition, the subtropical anticyclone axis may be tilted from the east-west orientation shown in Fig. 3, and seasonal displacements and amplitude changes in the subtropical anticyclone must be considered as well. Particularly during the early and late seasons, the midlatitude trough/ridge circulations may have such large amplitudes that a subtropical anticyclone cell will be suppressed, or the subtropical anticyclone axis is "broken" such that a direct connection is established between the midlatitude trough and the TC below the nominal anticyclone axis. The examples of operational NOGAPS analyses included in Chapter 3 will illustrate some of the variability of synoptic circulations in the Atlantic region.

One helpful feature in classifying the environment structure (synoptic pattern/region) is the position of the isotach maximum relative to the TC position, which is indicated in Fig. 3 as a shaded elliptical region. Given that the TC vortex is embedded in a steering current, the winds will be higher (lower) on the right (left) side looking in the direction of motion (Northern Hemisphere). Because 13 synthetic TC observations are inserted in the NOGAPS analysis whenever the NHC detects a tropical depression or stronger TC, and (since October 1994) the average of these 13 observations is adjusted to equal the past 12-h storm motion, the position of the isotach maximum is a proxy for the steering flow. This assumes that enough observations exist over the Atlantic to define the environmental flow, which is nearly always the case. As an example, the isotach maximum is expected to be on the northern side of a TC that is translating westward in the Tropical Easterlies (TE) of the Standard pattern (Fig. 3), and be on the northeastern side as the TC moves northwestward in the Poleward Flow (PF) region of the Standard pattern. If the TC fails to recurve and begins to move south of west in the Equatorward Flow (EF) region of the Standard pattern, the isotach maximum will suddenly shift to the west-northwest of the TC. However, if the TC recurves through the subtropical anticyclone axis into the PF region of the Midlatitude pattern, the isotach maximum will be on the southeast side, and then on the southern side as the TC translates eastward in the Midlatitude Westerlies (MW) region of the Midlatitude pattern.

3. ENVIRONMENT STRUCTURE CHARACTERIZATIONS

Each of the synoptic pattern/region combinations that apply in the Atlantic will be described first as a conceptual model. Examples of NOGAPS analyses with the NHC positions will also be given. Although the streamlines in the conceptual models in Fig. 3 ideally represent the deep-layer steering flow appropriate for the present TC intensity (shallower for weaker storms), 500-mb NOGAPS analyses are normally used for convenience. Since the environmental steering by definition excludes the TC circulation, the forecaster must qualitatively infer the streamline flow after mentally removing the TC circulation. The goal here is only synoptic map typing, and not to derive *quantitative* estimates of steering, which would require more precise vertical layer choices and an explicit decomposition of the vortex and environment.

a. Standard synoptic pattern

1. Conceptual model. In the Standard (S) synoptic pattern (Fig. 3, bottom), the axis of the subtropical anticyclone is approximately east-west. As indicated in Chapter 2, it also may be slightly tilted longitudinally and a variety of midlatitude circulation orientations may be found poleward of the subtropical anticyclone axis. If the midlatitude ridge is in phase with the subtropical ridge, a more meridional orientation will result. A "break" in the subtropical anticyclone axis may be present in association with a passing midlatitude trough. A zonally oriented monsoon trough is also included in the S synoptic pattern, with equatorial westerlies between the Equator and the monsoon trough, and trade easterlies between this trough and the subtropical anticyclone. Compared to all other TC basins, this monsoon trough tends to be a smaller factor in Atlantic TC formation, and no TCs formed in the equatorial westerlies during 1990-1998.

Four synoptic regions are defined in the S pattern (Fig. 3). If a TC would have formed in the Equatorial Westerlies (EW) region in the Atlantic, it would initially have had a west-to-east track. Rather, the most common situation in the Atlantic is that a TC forms in the Tropical Easterlies (TE) region and has a basically east-to-west track, and the isotach maximum will then be on the poleward side. If the subtropical anticyclone has a significant tilt away from a zonal orientation, the track of the TC in the TE region will have a similar deflection from an east-to-west orientation. As a TC in the Poleward Flow (PF) region of the S pattern moves around the southwest flank and into the break between the subtropical anticyclone cells, the translation speed will decrease if the two anticyclonic cells have roughly the same amplitude (i.e., the break region is a col). However, a TC moving around the Bermuda high with a weaker high over the U. S. may not have a decrease in translation speed. As the track turns poleward in response to the northwestward and then northward environmental steering, the isotach maximum will rotate to be northeast and then east of the TC center. A TC in the PF region may move into the Equatorward Flow (EF) region of the S pattern if the western subtropical anticyclone cell builds eastward, or a midlatitude ridge moves poleward of the break and blocks the path of the TC toward the north. As the TC then moves westward, or even south of west, a "stairstep" track is said to have occurred. When the subtropical anticyclone is rather distorted over the Atlantic, it is also possible for a TC to form in the EF region and have a south-of-west initial motion.

2. Analysis examples. Representative NOGAPS streamline and isotach analyses for a TC in the Standard/Tropical Easterlies (S/TE) pattern/region combination are shown in Fig. 4a. Hurricane Georges is near 15°N, 52°W and is moving toward 289° at a translation speed of 15 kt. This track direction is consistent with the extensive, east-west subtropical anticyclone to the north. Even though a vigorous midlatitude trough is passing farther north, the strength of the subtropical anticyclone prevents any break from forming and the steering flow for the TC is westward. Just as Hurricane Georges had earlier formed in an African wave, Tropical Depression (TD) 09 (pre-hurricane Ivan) has formed near 13°N, 28°W in the next wave in the series. This TD also is moving westward (280°) in a S/TE pattern/region combination.

Two TCs are also in the S pattern in Fig. 4b. Hurricane Bonnie is near 33°N, 78°W and is moving toward 346° at 9 kt. Whereas Bonnie had been moving at 13 kt just 24 h earlier, it is clearly moving into a col region between two nearly equal strength subtropical anticyclone cells. However, the poleward steering flow associated with the eastern cell is stronger, as indicated by the larger isotach maximum to the east. Thus, Bonnie is in the S/Poleward Flow (PF) pattern/region. Meanwhile, Hurricane Danielle is near 19°N, 51°W and is moving toward 290° at 19 kt. Danielle is clearly in a S/TE pattern/region with a strong subtropical anticyclone to the north, and the isotach maximum is on the north side of the TC as in the conceptual model (Fig. 3).

Another example of two TCs equatorward of two subtropical anticyclone cells is given in Fig. 4c. Whereas Tropical Storm (TS) Iris, which is the western TC near 15°N, 57°W, is moving toward 260° at 9 kt, Hurricane Humberto is moving toward 330° at 8 kt. A classification of Iris in the S/Equatorward Flow (EF) pattern/region as in the conceptual model (Fig. 3) is consistent with the south-of-west track in response to a steering flow associated with anticyclonic circulations to the west and northwest.

An alternate explanation for the equatorward displacement of Iris is the Semi-direct Cyclone Interaction (SCI) transitional mechanism (Fig. 2, lower right), which is a generalization of the binary TC interaction of Carr *et al.* (1997). As illustrated in the conceptual model of the SCIW mechanism (Fig. 5a), an equatorward steering flow across the western TC (Iris) is established between the high pressure to the northwest and the low pressure associated with Hurricane Humberto to the east. In this case, the poleward deflection of Hurricane Humberto is also consistent with a SCIE mechanism (Fig. 5b), such that the low pressure of Iris and the high pressure of the eastern subtropical anticyclone establishes a poleward steering flow across the eastern TC (Humberto).

In the original Carr and Elsberry (1994) description of the Systematic Approach, the SCI mechanism as described in Fig. 5a-b was also labeled as a Multiple TC synoptic pattern. This terminology has been discarded, because the introduction of the EF and PF regions of the Standard pattern as in Fig. 3 completely subsumes the Multiple TC pattern when separate TCs are present in the two regions. The Iris-Humberto case (Fig. 4c) is an illustration. However, the new Standard conceptual model in Fig. 3 is more general in that it allows for cases in which only one TC is present in either the PF or the EF region.

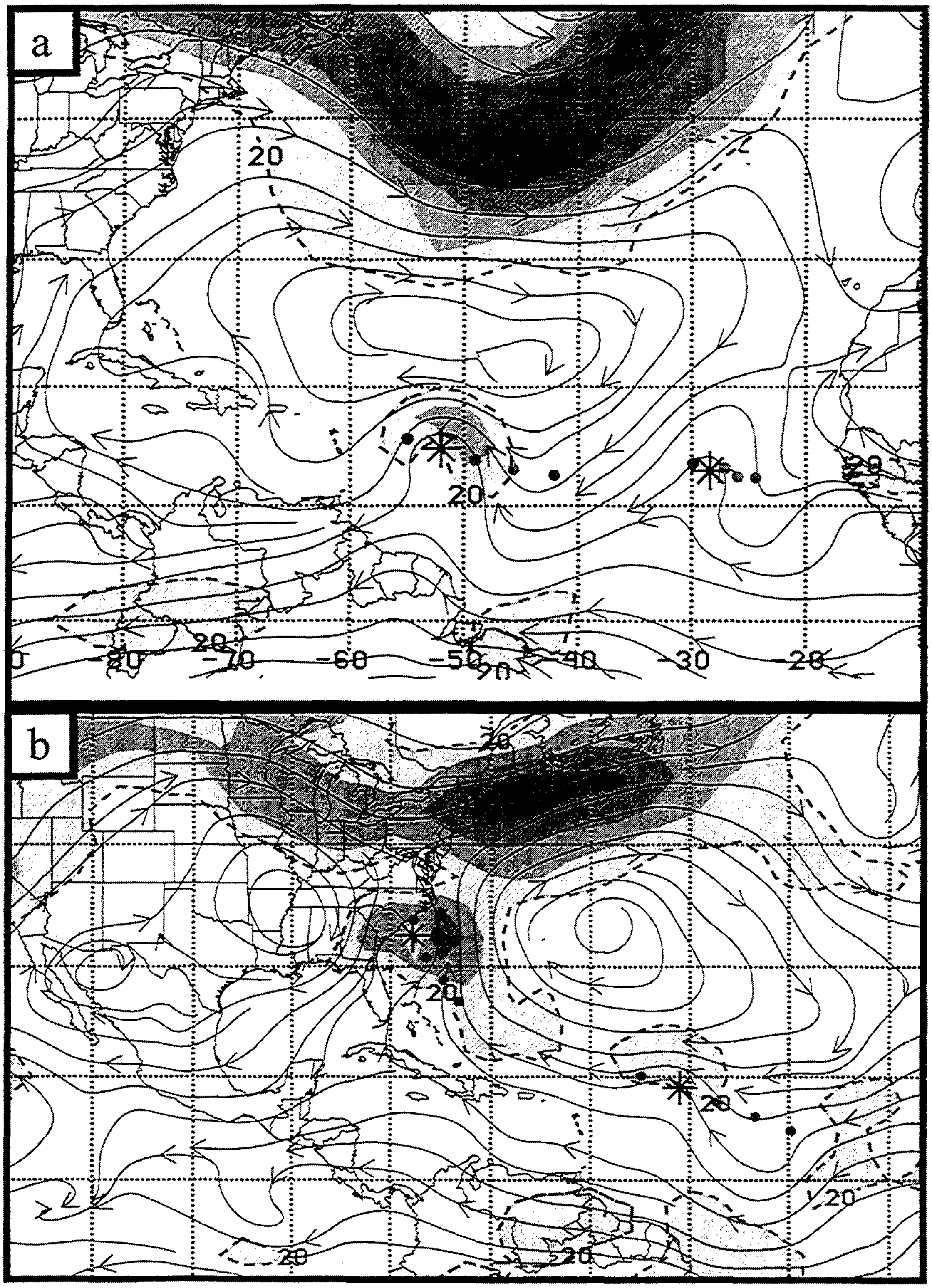


Fig. 4 (a) Streamline (thin lines) and isotachs (kt; shaded with 10-kt interval beginning with 20 kt, which is heavy dashed line) for 1200 UTC 19 September 1998 NOGAPS 500-mb analysis. Positions of Hurricane Georges and Tropical Depression 09 are shown by asterisks near 15°N, 52°W and 13°N, 28°W respectively. Dots to the west (east) of the asterisks indicate the future 12-h (past 12-h, 24-h, and 36-h) positions of the TCs (if available). (b) As in Fig. 4a, except for 1200 UTC 26 August 1998 and Hurricane Bonnie (Danielle) is the western (eastern) TC.

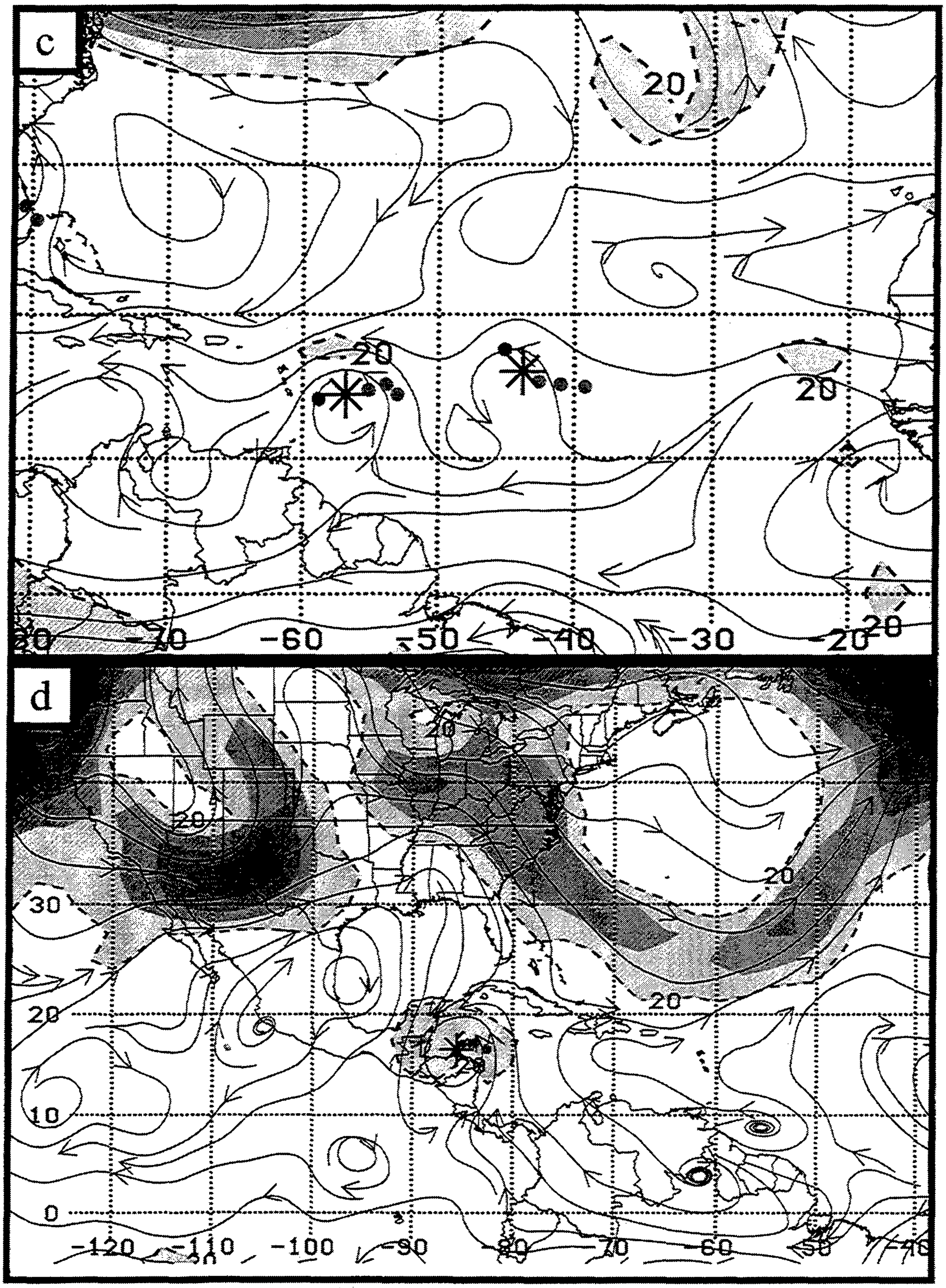


Fig. 4 (c) As in Fig. 4a, except for 0000 UTC 25 August 1995 and TS Iris (Hurricane Humberto) is the western (eastern) TC. (d) As in Fig. 4a, except for 0000 UTC 28 October 1998 and Hurricane Mitch.

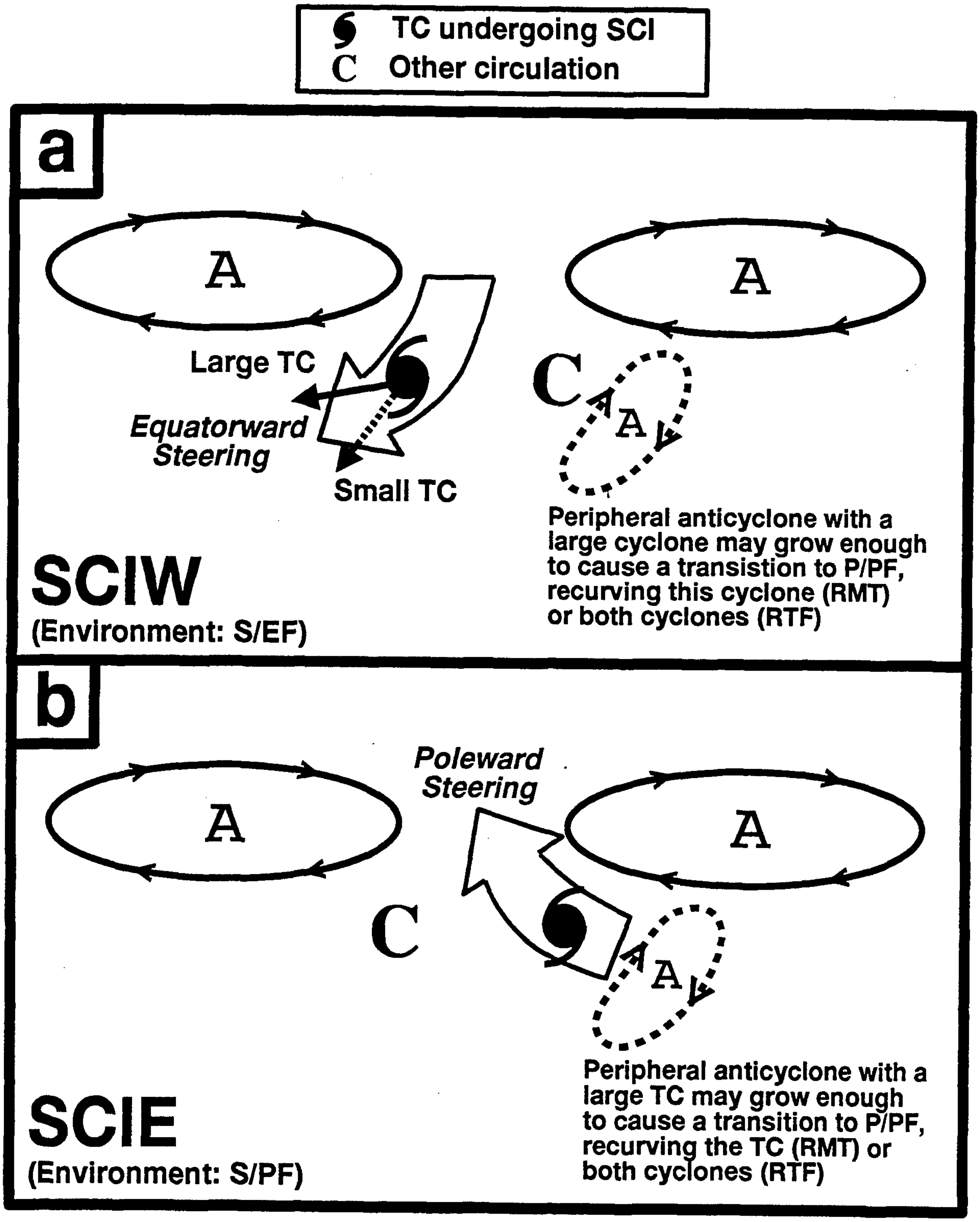


Fig. 5 Conceptual models for the Semi-direct Cyclone Interaction (SCI) transitional mechanism causing track deflections on the (a) western TC (SCIW) or (b) eastern TC (SCIE) owing to steering flows (large open arrows) established by pressure gradients between adjacent high pressure in the subtropical anticyclone and low pressure in the other cyclone. See Carr *et al.* (1997) for further description and examples.

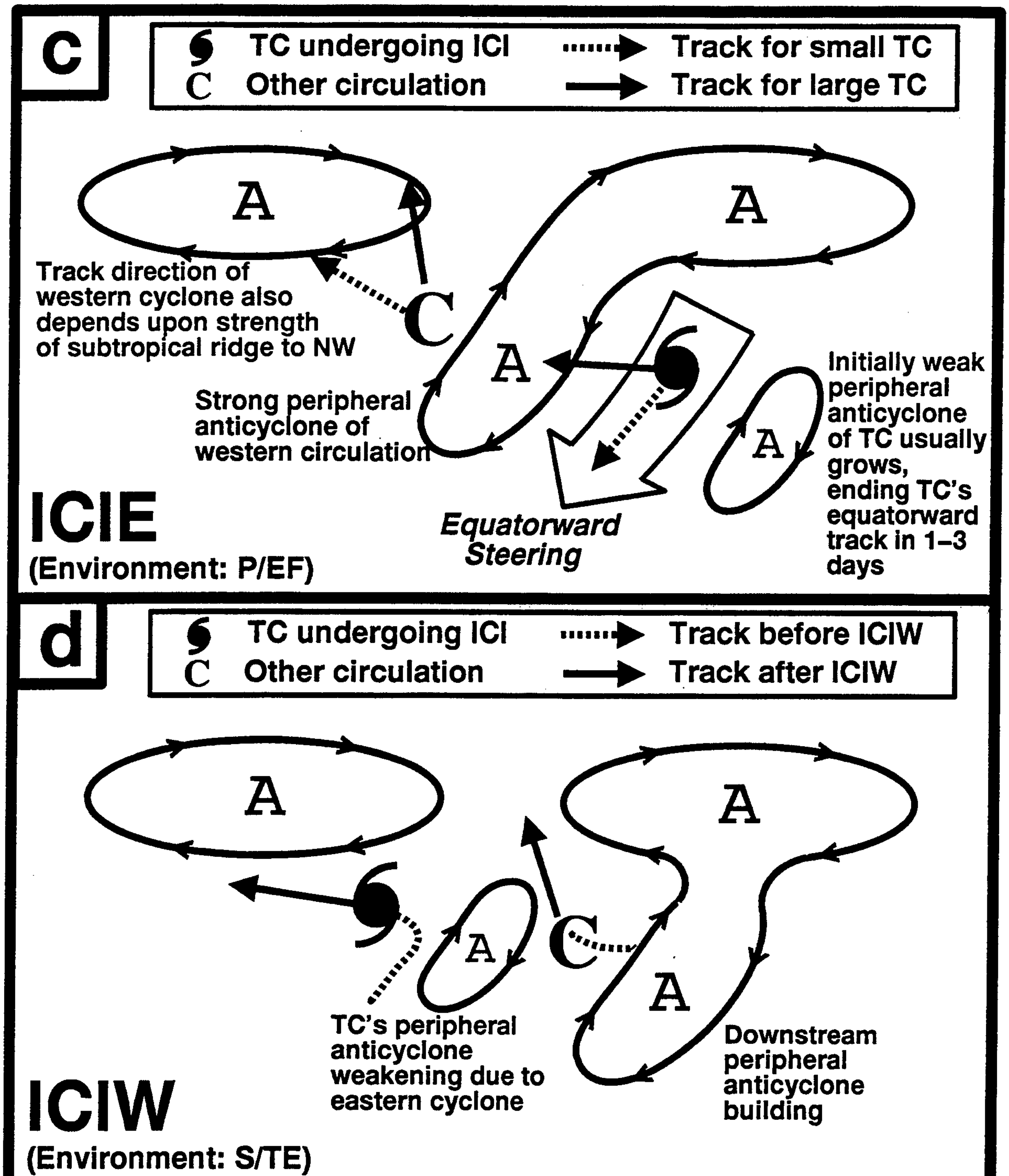


Fig. 5 (continued) Conceptual models as in Fig. 5a-b except for Indirect Cyclone Interaction (ICI) transitional mechanism on the (c) eastern TC (ICIE) or on the (d) western TC (ICIW). The key circulation is the peripheral anticyclone trailing the western cyclone (or TC). In the ICIE, the amplitude of the intervening anticyclone is growing or is maintained such that an equatorward steering flow is imposed on the eastern TC, which is then in the P/EF pattern/region. In the ICIW, the approach of the eastern cyclone (or TC) diminishes the intervening anticyclone, and thus diminishes the poleward steering flow over the western TC, which may then turn westward in a transition from P/PF to S/TE.

A third explanation for the equatorward displacement of Iris is the Indirect Cyclone Interaction (ICI) mechanism in the TC-Environment transformations in Fig. 2 (bottom right), which again is a generalization of the binary TC interaction of Carr *et al.* (1997). As in the ICIE conceptual model (Fig. 5c), a large amplitude wave (cyclone) is located about 17° long. to the west with an intervening anticyclone. Since the intervening anticyclone to the west of Iris is the peripheral anticyclone of the western cyclone, Iris may be considered to be under the steering influence of this peripheral anticyclone, which contributes to an equatorward deflection (ICIE). For completeness, the ICIW conceptual model is shown in Fig. 5d since will be employed later. In the ICI model, the eastern cyclone may also be another TC as in Carr *et al.* (1997).

The final S pattern example is a late-season TC with vigorous midlatitude circulations and a distorted subtropical anticyclone (Fig. 4d). Hurricane Mitch is moving slowly (3 kt) southward (toward 197°). The subtropical anticyclone cell to the east has been displaced southward by a deep midlatitude trough to the north of Mitch. A southwest-to-northeast oriented subtropical anticyclone is to the west and northeast of Mitch. As implied by the equatorward motion, the anticyclonic cell to the northwest (centered at 23°N, 97°W) must have a stronger steering influence on Mitch than the cell to the southeast. A classification of S/Equatorward Flow (EF) is most appropriate for this case. Notice that in conjunction with the midlatitude trough over the western U. S., a wavetrain of alternating cyclones and anticyclones oriented northwest-to-southeast includes Mitch. That is, an alternate interpretation of the scenario in Fig. 4d is that the ICIE transitional mechanism (Fig. 5c) is occurring in which the western cyclone is the midlatitude trough. In that interpretation, Mitch would be in a transition to the P/EF pattern/region. Whether Mitch is in the S/EF or the P/EF pattern/region, the key to its future motion is the strength of the anticyclone to the northwest. A plausible hypothesis for the subsequent equatorward track of Mitch over Central America (where it caused enormous damage and loss of life) is that energy flux from the midlatitude trough to the subtropical anticyclone to the northwest of Mitch continued its dominant steering flow influence on Mitch.

3. Tracks. Although it is theoretically possible to have an Atlantic TC in the S/EW pattern/region, this was not observed during the 1990-98 study period. All tracks while the TCs were in the S/TE pattern/region, which is 30.5% of the 1568 cases in the sample, are shown in Fig. 6a. The S/TE tracks in the eastern Atlantic are associated with African wave formations in a relatively narrow latitudinal band. Many of the tracks have long paths that are slightly north of west, as would be expected from a beta-effect propagation (Carr and Elsberry 1997) even if the steering flow was zonal. Formations of TCs farther west occur in a broader latitudinal band, but also have consistent westward tracks. As demonstrated by Carr and Elsberry (1997) and illustrated schematically by the TC motion arrows in Fig. 5a and 5c, larger TCs with stronger outer circulations have a larger beta-effect propagation toward the west and poleward. Although the Beta-Effect Propagation (BEP) is listed as a transitional mechanism in Fig. 2 (bottom right), it is always present to some degree. It is understood that the total motion includes both the steering flow and the BEP, and a larger TC in the S/TE pattern/region will be deflected poleward more rapidly.

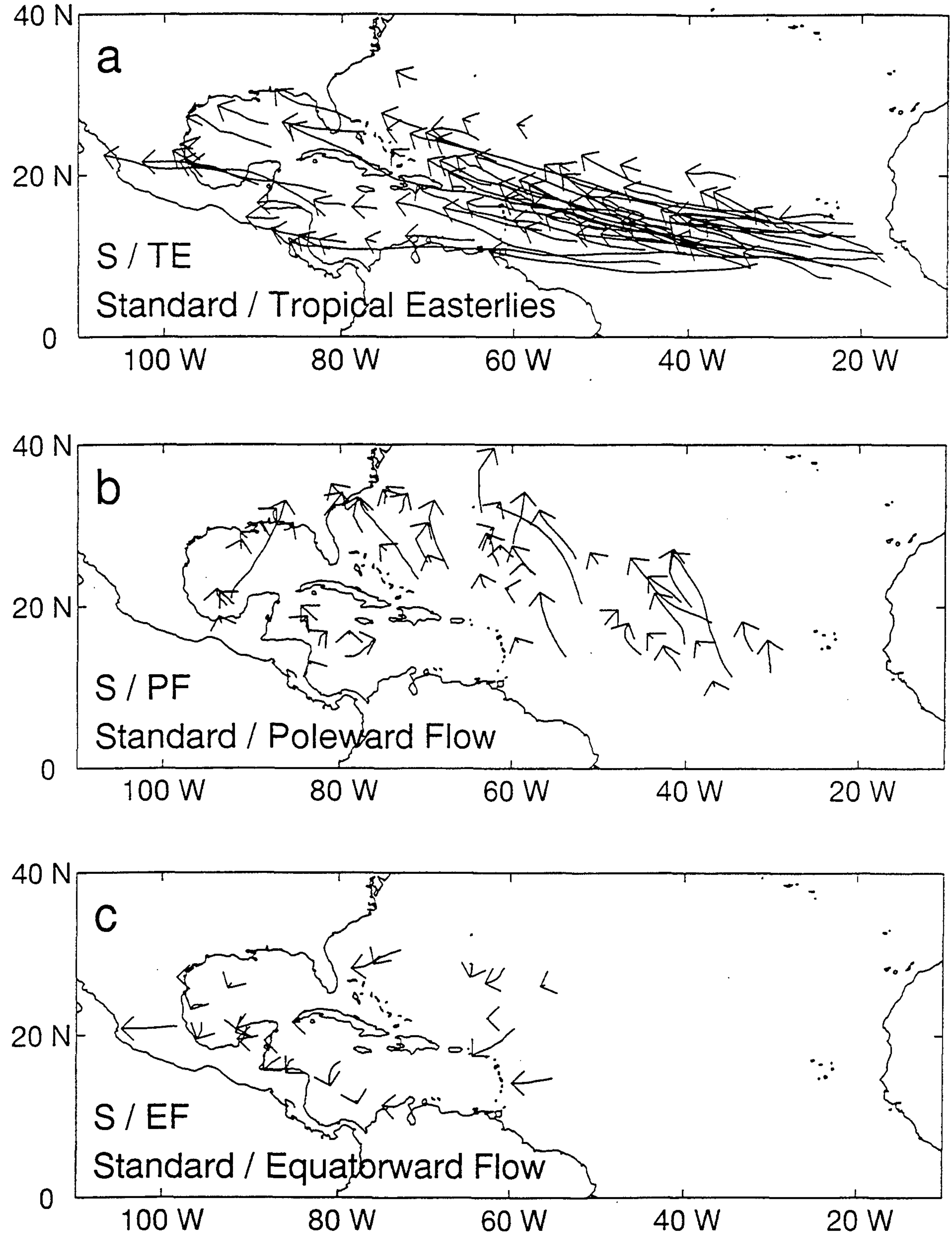


Fig. 6 Track segments during which the TC is in the Standard (S) synoptic pattern and the (a) Tropical Easterlies (TE), (b) Poleward Flow (PF), and (c) Equatorward Flow (EF) regions. Each track segment ends at the arrow head.

Tracks while the TCs are in the S/PF pattern/region (12.6% of all cases) are illustrated in Fig. 6b. As indicated in the S pattern conceptual model (Fig. 3), TCs in the PF region are beginning to turn poleward toward a break in the subtropical anticyclone axis. If this axis is oriented east-west, the PF tracks would have directions between 315° and 360°, and this is the case with many of the TC tracks in Fig. 6b. In other cases, the subtropical anticyclone is oriented northwest to southeast and the TC may have an east-of-north track segment before the TC reaches the subtropical anticyclone axis and thus leaves the Standard pattern. Although most of the S/PF tracks are relatively short, about 10 of the tracks during this nine-year period had considerably longer paths. These anomalous S/PF tracks reflect the variability in meridional extents of the subtropical anticyclone in the Atlantic. That is, the TC in S/PF may have a longer track along the southwestern flank of a broad meridional subtropical anticyclone.

In the 4.8% of all cases in which the TC was in the S/EF pattern/region, the track segments are generally short and are oriented just south of west. Some exceptions are a few anomalously equatorward paths in the southwestern Caribbean Sea as in the Hurricane Mitch case in Fig. 4d. Attention is drawn to the differences in track orientation and length between the S/EF pattern/region (Fig. 6c) and the more common S/TE pattern/region (Fig. 6a). Clearly, such differences are important to the track forecast, and it is thus important that the forecaster recognize the anomalous synoptic conditions leading to a S/EF track.

The total number of track segments in the S pattern among these three synoptic regions is 47.5% of the 1568 cases during 1990-98. Although this large fraction of the total sample clearly justifies the "Standard" label, the variability among the track segments in Fig. 6a-c is a reflection of the variability in the Atlantic subtropical anticyclone amplitudes and orientations, as well as the seasonal displacements in the subtropical high pressure. The operational analyses in Fig. 4 give examples of this variability in the S pattern. Thus, the conceptual model of the S pattern in Fig. 3 must only be regarded as a flexible template.

b. *Poleward synoptic pattern*

1. Conceptual model. In the Poleward (P) synoptic pattern (Fig. 3, middle left), the environment structure usually has a significant break in the subtropical anticyclone axis poleward of the TC and a prominent, primarily poleward-oriented anticyclone to the east that extends equatorward of the TC. In the original Carr and Elsberry (1994) conceptual model for the P pattern, the anticyclone to the east was attributed to the Rossby wave dispersion from a large TC. It was thus termed a peripheral anticyclone to emphasize the direct connection to the TC circulation, including the tendency for the eastern anticyclone cell to translate poleward with the TC, which tended to maintain a more poleward track rather than a northeastward post-recurvature track.

Two modifications recently have been made in the original Carr and Elsberry (1994) P pattern model. First, the eastern anticyclone has been extended equatorward to account for the presence of the Equatorward Westerlies (EW) synoptic region (Fig. 3), in which the TC has a more eastward component in addition to a poleward component. Although rarely observed in this Atlantic sample, this P/EW is analogous to the South Pacific Convergence Zone (Bannister *et al.* 1997, 1998).

A second modification of the original P pattern has been to add a separate Equatorward Flow (EF) synoptic region to the east of the peripheral anticyclone (Fig. 3). The TC in this region is depicted with an open symbol to emphasize that this is a separate TC from the western TC that may be generating the peripheral anticyclone. However, an eastern TC is not required for the western TC to be classified in the P/PF (or P/EW) pattern/region. Although the presence of the eastern cyclone in this downstream position in the Rossby wave train is often observed, the physics of this process are not well understood. A critical factor in the motion of the eastern TC is that the peripheral anticyclone of the western TC establishes a steering flow across the eastern TC so that it has an equatorward component relative to the climatological track expected south of the subtropical anticyclone. Establishment of this western TC-peripheral anticyclone-eastern TC triplet is thus the Indirect Cyclone Interaction (ICI) transitional mechanism illustrated in Fig. 5c-d.

More recent studies (Carr and Elsberry 1999) have indicated that the western circulation in the triplet does not necessarily have to be a TC. Rather it may be a large tropical depression, or even a midlatitude trough penetrating into the subtropical anticyclone. Whenever ICI occurs, the potential exists for changes of the environment structure, and thus in the TC track. Carr and Elsberry (1999) demonstrate that numerical model TC track forecasts often have a difficult time predicting this situation, and thus may lead to erroneous guidance.

2. Analysis examples. The case of Hurricane Erika in the Poleward Flow (PF) synoptic region of a Poleward (P) pattern (Fig. 7a) resembles the conceptual model (Fig. 3) rather well. Notice the wide break in the subtropical anticyclone axis with one well-defined cell over the southeastern U. S. and a weak cell with a center near 26°N, 56°W. This break is clearly associated with a midlatitude trough near 70°W. Even though Hurricane Erika (90 kt) is still south of the subtropical anticyclone axis, it is moving due north at 6 kt. Questions that might be asked: (i) How can the midlatitude trough far to the northwest be causing a poleward motion? (ii) Given the weak subtropical anticyclone cell to the northeast, how is it contributing to the poleward motion? The alternate explanation is that the extended peripheral anticyclone to the east and southeast of Erika is responsible for the poleward motion. Notice the isotach maximum to the east-southeast of Erika is consistent with a steering flow that, in conjunction with a northwestward beta-effect propagation, can account for a poleward steering flow.

While the forecaster would certainly be concerned with the eastward translation and possible deepening of the midlatitude trough, another key to the future motion of Erika is the continuation of the peripheral anticyclone to the east and southeast. Indications of subsidence and clearing of any deeper convection to the southeast in the water vapor (and perhaps IR) imagery would be a symptom of upper-level subsidence that will sustain or intensify the peripheral anticyclone. Since the Rossby wave dispersion that creates this peripheral anticyclone has a larger amplitude for larger cyclones (Carr and Elsberry 1997), it is important that a numerical model used for TC track guidance has the correct outer wind structure in the initial conditions.

Another example of the P/PF pattern/region is the Hurricane Luis case (Fig. 7b). Notice the midlatitude cyclone in the northern Gulf of Mexico has created a break in the subtropical anticyclone. However, a strong anticyclone cell is to the northeast near 32°N, 59°W and a thin

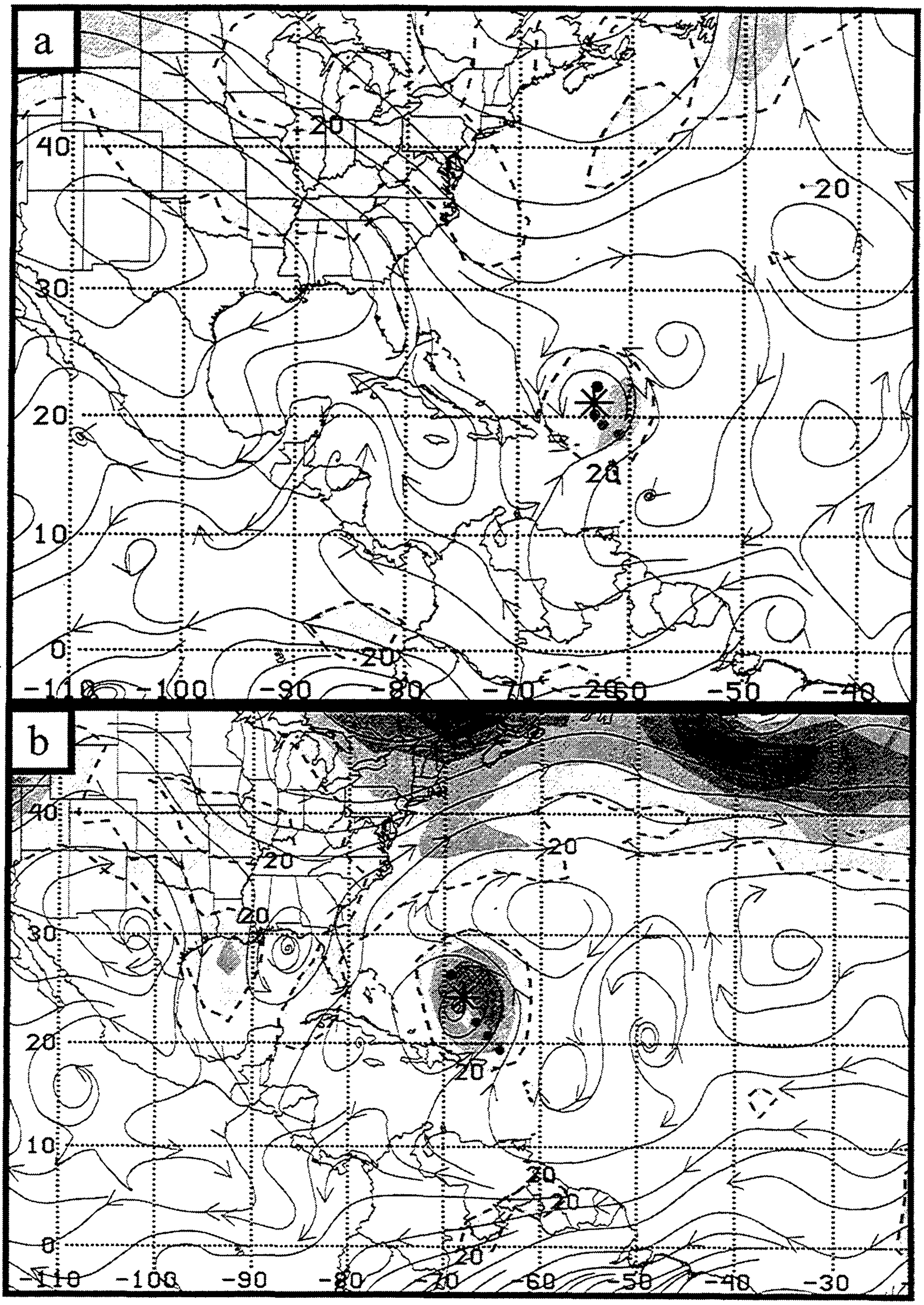


Fig. 7. NOGAPS 500-mb analyses as in Fig. 4, except at (a) 0000 UTC 8 September 1997 for Hurricane Erika, (b) 0000 UTC 8 September 1995 for Hurricane Luis.

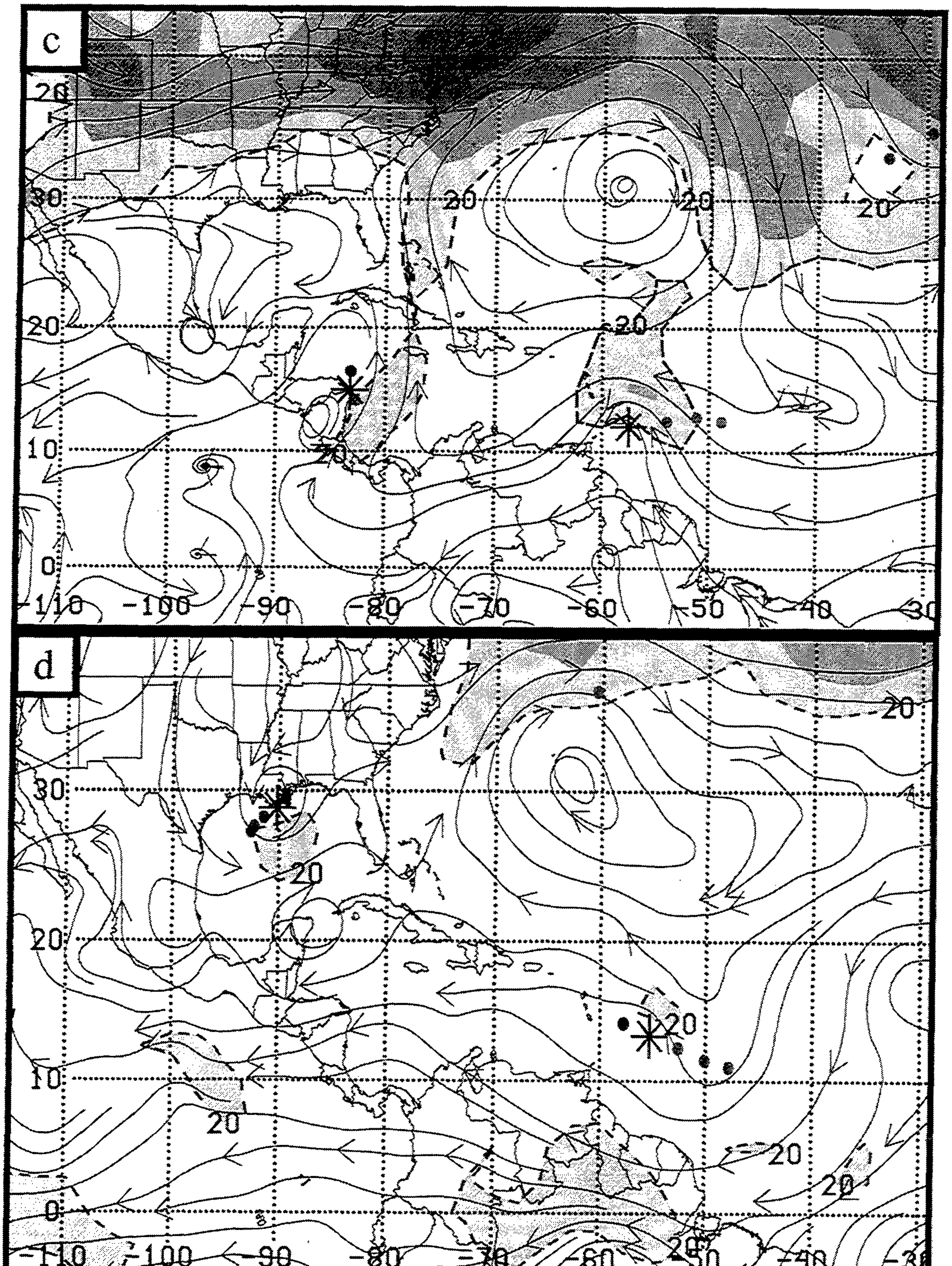


Fig. 7. (continued) NOGAPS 500-mb analyses as in Fig. 4, except at (c) 1200 UTC 8 October 1995 for (western) TD 19 (later Hurricane Roxanne) and (eastern) TD Pablo, and (d) 0000 UTC 18 July 1997 for (western) TS Danny and (eastern) TD 05.

ridge remains between Luis and the midlatitude trough. Hurricane Luis (110 kt) is moving toward 334° at 17 kt even though it is well south of the subtropical anticyclone axis. The poleward (clockwise of 315°) heading during the past 24 h is attributed to a peripheral anticyclone that extends equatorward to the east and southeast of Hurricane Luis as in the P conceptual model (Fig. 3).

This peripheral anticyclone would have been even more intense had it not been for the presence of a cyclone to the east (near 20°N, 50°W) that is a downward extension of an upper-tropospheric low. Had this been a TC, this cyclone would have been in the P/EF pattern/region of the conceptual model (Fig. 3). In addition, the cyclone-anticyclone-cyclone triplet is analogous to the Indirect Cyclone Interaction (ICI) model in Fig. 5c-d. In the ICIW model with only one TC and one cyclone, Hurricane Luis is the western TC and the upper-tropospheric low is the eastern cyclone. Because Luis' poleward motion is not as large as it might have been if its peripheral anticyclone had not been eroded by the cyclone to the east, this is then an ICIW situation (Fig. 5d).

Future motion of Luis then depends on the subtropical anticyclone to the northeast, the peripheral anticyclone to the southeast, the upper-tropospheric trough to the east, as well as the midlatitude trough to the west. Clearly, the possibilities for improper representations of these multiple circulations involved in the motion of Luis in the initial conditions of the different numerical models means a variety of tracks may be predicted, which is a difficult situation for the forecaster.

An example of an ICIE (Fig. 5c) with two TCs in which the eastern TC is being deflected equatorward in the EF synoptic region of the P pattern (Fig. 3) is presented in Fig. 7c. The western TC (eventually Hurricane Roxanne) is at this time only a tropical depression, in part because its western circulation is over land. This depression is clearly in a P/PF pattern/region with an extended peripheral anticyclone to the east and southeast. The isotach maximum is to the east, which indicates a steering flow to the north, and this is consistent with a track toward 347° at 5 kt. TS Pablo is to the east of this peripheral anticyclone, and has been moving south of west (toward 263°) at 18 kt. Although the southward deflection is small, this is still a departure from the expected climatological track (e.g., as in the common S/TE pattern/region tracks in Fig. 6a) equatorward of a strong subtropical anticyclone cell. Given the south-of-west motion, one would have expected the isotach maximum to be north-northwest of the TC, so that the NOGAPS analysis may be a little suspicious in this case.

An example of the rare occurrence of an Equatorial Westerlies (EW) synoptic region of the P pattern (Fig. 3) is given in Fig. 7d. While the equatorial designation may be considered to be a "stretch" when the TC is near 29°N, the synoptic pattern of an east-west oriented anticyclone to the south of the TC and an isotach maximum to the south agrees well with the P/EW pattern/region conceptual model. The midlatitude trough that had established a break in the subtropical anticyclone axis has passed to the northeast. Whereas flow on the backside of this midlatitude trough might have been expected to translate the TC toward the southwest, Tropical Storm (TS) Danny is moving toward 58° at 6 kt toward landfall in the southeastern U.S., which is consistent with the expected TC motion in the P/EW pattern/region.

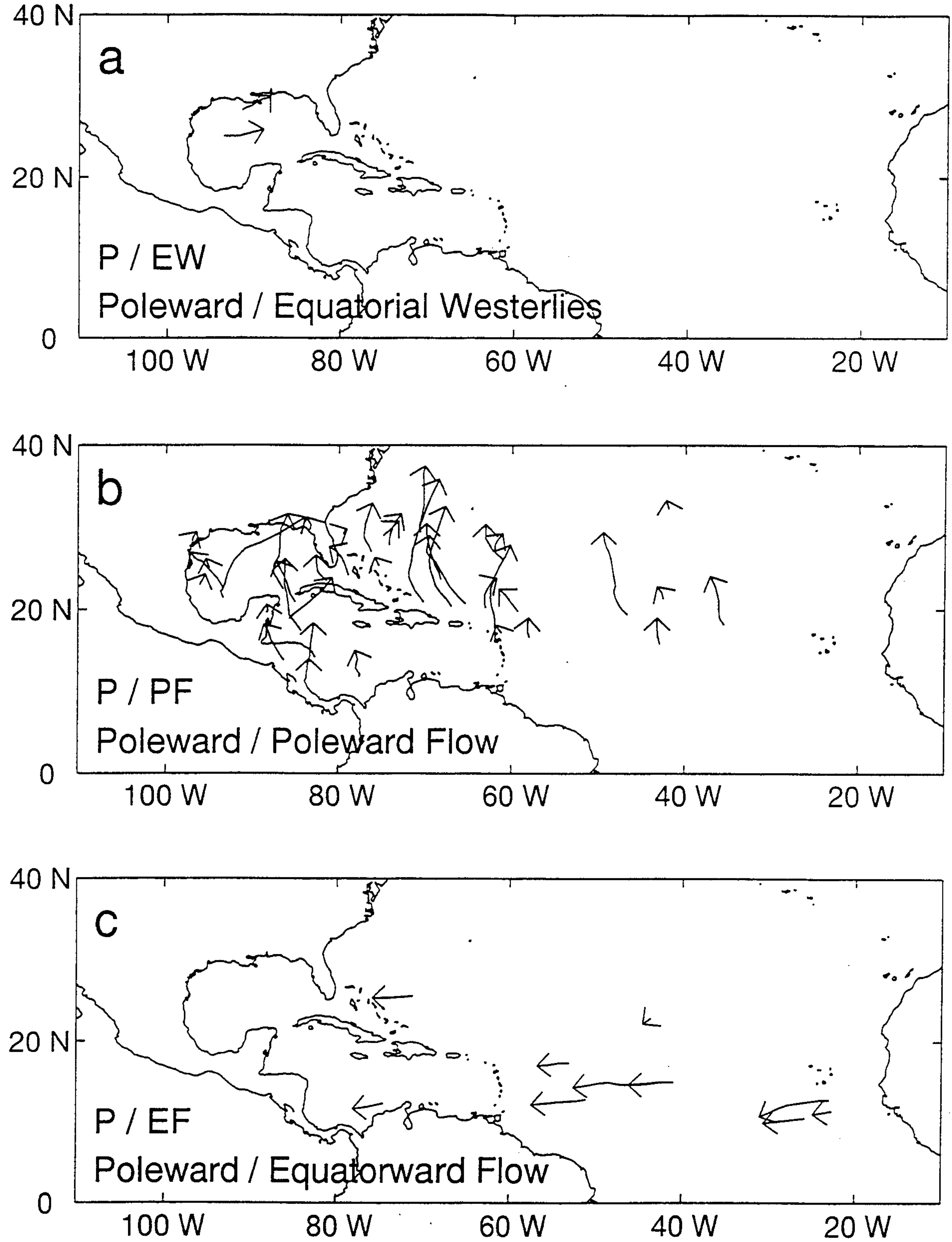


Fig. 8. Track segments as in Fig. 6, except during periods when the TC is in the Poleward (P) synoptic pattern and the (a) Equatorial Westerlies (EW), (b) Poleward Flow (PF), and (c) Equatorward Flow (EF) regions.

TD 05 is also depicted in Fig. 7d near 13°N, 55°W, and is moving toward 289° at 13 kt while in the S/TE pattern/region south of the subtropical anticyclone. Unlike TS Pablo east of pre-Roxanne in the previous example, TD 05 is east of TS Danny by more than 30° lat., which is the maximum separation for an ICIE transformation. Hence, TD 05 is moving north of west in the S/TE environment rather than south of west in a P/EF environment. Actually, the depression is just beginning to develop a peripheral anticyclone to the southeast along 50° W. If this peripheral anticyclone continues to develop and the isotach maximum shifts from north to northeast, a transition toward a P/PF environment will occur via the RMT transformation. However, TD 05 soon decays and the transition process does not progress enough for the environment to be classified as even transitional from S/TE toward P/PF.

3. Tracks. As indicated above, the P/EW pattern/region is rarely observed in the Atlantic (0.6% of the 1568 cases during 1990-98). Only two cases (Danny during 1997, Fig. 7d; TD 10 during 1996) are shown in the P/EW track summary (Fig. 8a), and both TCs moved eastward in the Gulf of Mexico.

The most common (11.2% of all cases) tracks in the P pattern are in the PF region (Fig. 8b). As implied by the designator, these tracks are poleward, and tend to be sinuous with some indication of anticyclonic curvature, especially in the longer tracks. A more persistent poleward track would be expected if the peripheral anticyclone to the east is more intense and translates poleward with the TC. As indicated in the P pattern conceptual model (Fig. 3), the P/PF tracks are terminated if the TC passes through the subtropical anticyclone axis, so that many of these tracks end around 30°N. As indicated previously, the Atlantic subtropical anticyclone circulation is often tilted and distorted by interaction with the midlatitude circulations, so that the subtropical anticyclone axis may not always be near 30°N.

Only 1.7% of all cases during 1990-98 were in the P/EF pattern/region. Nevertheless, these south-of-west tracks (Fig. 8c) are a departure from the climatological track, and the forecaster should be alert for these anomalous conditions. These P/EF tracks typically are east of a pre-existing peripheral anticyclone associated with a TC (or other cyclone) to the west that is moving poleward in the P/PF pattern/region (Fig. 8b). Because the key to the persistence of the south-of-west track in the P/EF pattern/region is this peripheral anticyclone, which may also be moving poleward with the western TC, it is not surprising that these conditions do not persist long, and thus the P/EF tracks (Fig. 8c) are not long.

c. Upper-level low synoptic pattern

1. Conceptual model. The Upper-level (U) low synoptic pattern (Fig. 3, middle right) is a generalization of the Low pattern in the preliminary study by Kent (1995). One of the reasons for this generalization is the common presence of mid-tropospheric lows that have penetrated downward from an upper-tropospheric trough in the eastern and central Atlantic. Even though these cold-core systems are decreasing in intensity toward the surface, the associated circulation in the mid-troposphere may determine the steering flow over the TC. As indicated in the schematic (Fig. 3), the trough in which the U low is embedded typically has a northeast-southwest tilt, with similarly tilted ridges (or closed anticyclones) to the northwest and southeast. If the TC is between the trough and the northwest anticyclone, the steering flow will be

westward and equatorward, which is the Equatorward Flow (EF) synoptic region. If the TC is between the trough and the anticyclone to the southeast, the steering flow will be eastward and poleward, which is the Poleward Flow (PF) synoptic region. Notice the isotach maximum will be to the northwest (southeast) of the TC in the EF (PF) synoptic region (Fig. 3), as the TC motion is toward the southwest (northeast).

Whereas the trough in the U synoptic pattern is elongated in the schematic in Fig. 3, this pattern will also be applied if the trough is more circular. Examples will be shown in the next subsection.

2. Analysis examples. A typical example of the Upper-level (U) pattern in the eastern and central Atlantic is given in Fig. 9a. In this case, the trough extends from the western Mediterranean to the lesser Antilles. Notice also that the adjacent anticyclones to the northwest and southeast have a similar tilt. A tropical disturbance (20 kt) at 35°N, 50°W, which is the remnants of TC Marilyn after a period of vertical wind shear, is drifting westward. The storm in the U pattern is Noel, which at this time is near 20°N, 40°W. Although the isotach maximum is to the southeast of Noel, which indicates that the steering flow is consistent with a PF classification, Noel is moving so slowly ($\approx$ 1 kt) that the direction estimate is uncertain. This uncertainty is in part due to a Direct Cyclone Interaction (DCI) with a weak cyclone about 10° long. to the west. The DCI transitional mechanism (Fig. 2, bottom right) is a generalization of the Direct TC Interaction of two TCs as defined by Carr *et al.* (1997). As illustrated in the schematic (Fig. 10) with a western cyclone and an eastern TC that are close enough that their outer circulations overlap, a counter-clockwise rotation (Northern Hemisphere) of the two circulations occurs. The amount of rotation is dependent on the sizes of the two circulations and the separation distance. As demonstrated by Carr and Elsberry (1999), the dynamical models frequently erroneously merge the circulations later in the forecast so that the smaller of the two circulations may only appear as a lobe on the larger circulation. In reality, two cyclones only rarely merge.

An eastward track at 20°N in the central Atlantic is very non-climatological, since this is the latitude at which African waves might be expected to be amplifying and moving westward in the trades as in the S/TE pattern/region tracks (Fig. 6a). Clearly, it is the mid- and upper-tropospheric circulation patterns in Fig. 9a that are determining the motion of TC Noel.

A more circular upper-level low pattern illustrated in Fig. 9b is similar to the earlier Low synoptic pattern of Kent (1995). Notice that the central low near 33°N, 47°W is almost completely surrounded by anticyclonic circulations. TC Isidore is in the southeast quadrant of this low. The isotach maximum to the east of Isidore is consistent with a motion toward 15° at 14 kt, and a classification in the U/PF pattern/region.

Another elongated and tilted U pattern as in the conceptual model (Fig. 3) is presented in Fig. 11. A late-season TD Nicole has formed near 30°N, 26°W just 12 h earlier and is moving toward 234° at 11 kt. In addition, the isotach maximum is to the northwest of the TC, which is consistent with a U/Equatorward Flow (EF) pattern/region classification (Fig. 3).

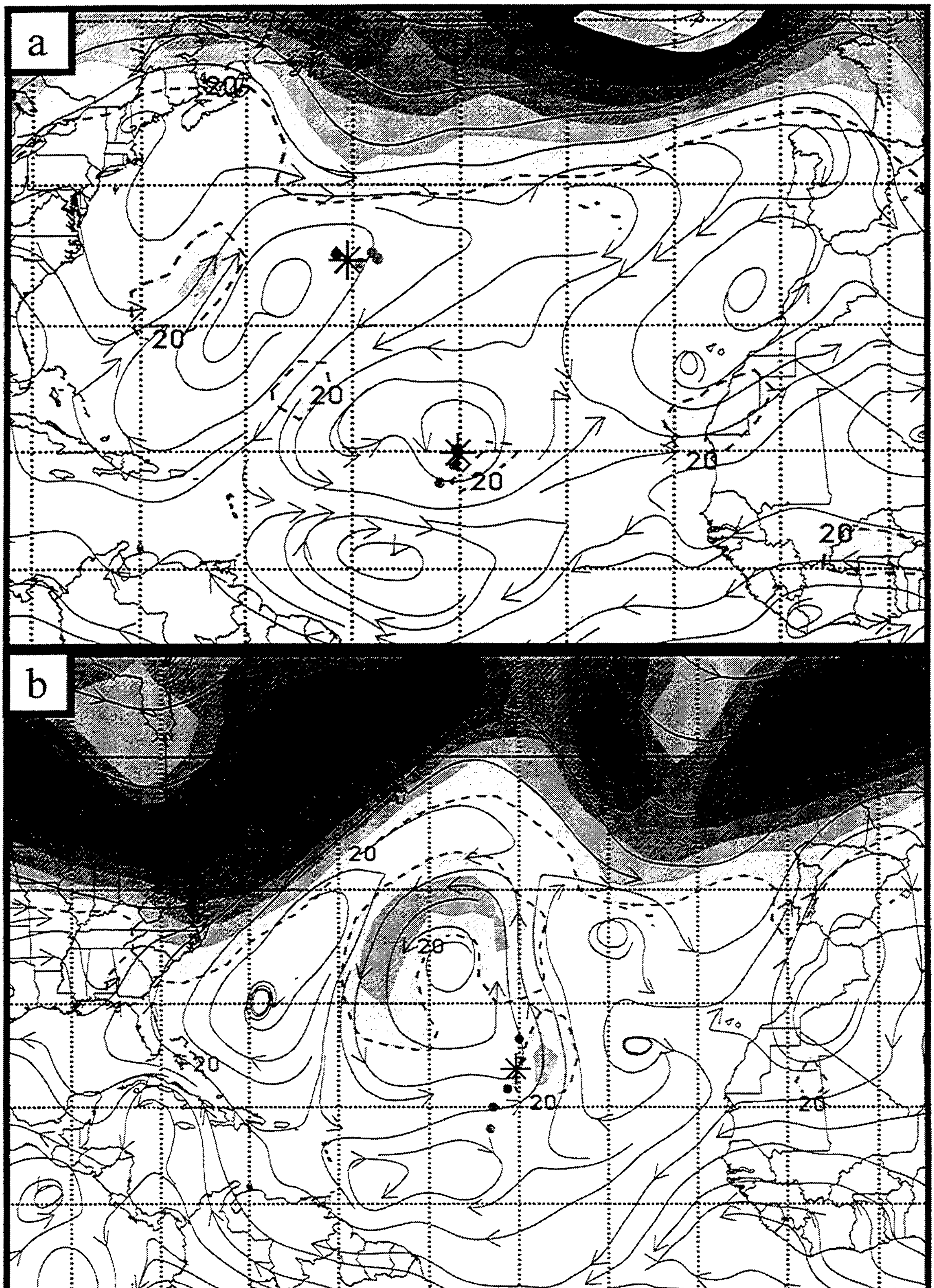


Fig. 9. NOGAPS 500-mb analyses as in Fig. 4, except at (a) 0000 UTC 1 October 1995 for TS Noel near 20°N, 40°W and TD Marilyn near 35°N, 50°W, and (b) 0000 UTC 30 September 1996 for TC Isidore.

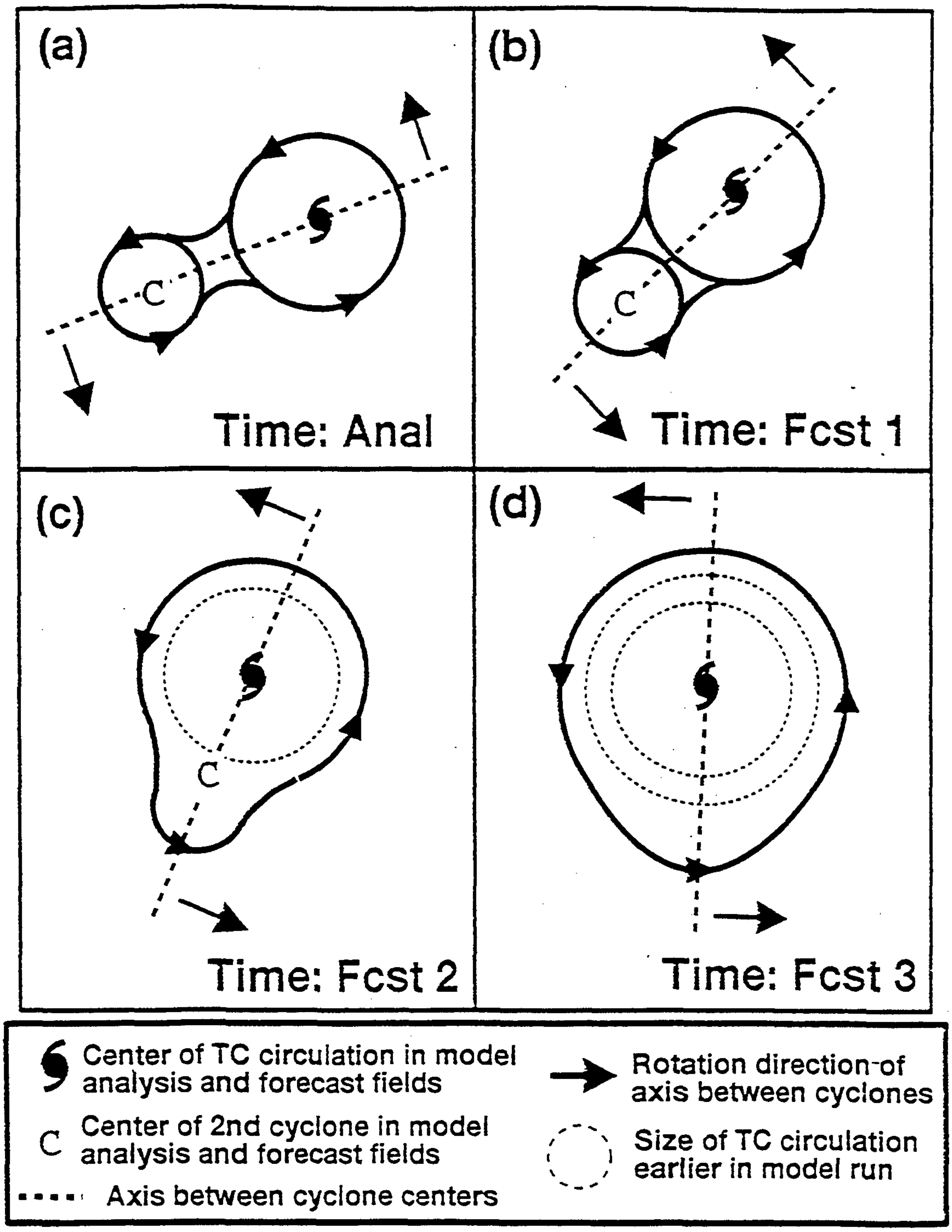


Fig. 10. Conceptual model of Direct Cyclone Interaction (DCI) in which a TC circulation interacts with another cyclone (C) to cause a counter-clockwise (Northern Hemisphere) rotation of the axis between the cyclone centers (heavy dashed like) and a possible merger of the two cyclones in which the combined circulation becomes larger with time (panels c and d). The TC may also be the smaller of the two cyclones, or the model may be applied to two TCs of similar sizes in which the tracks of both TCs will be affected.

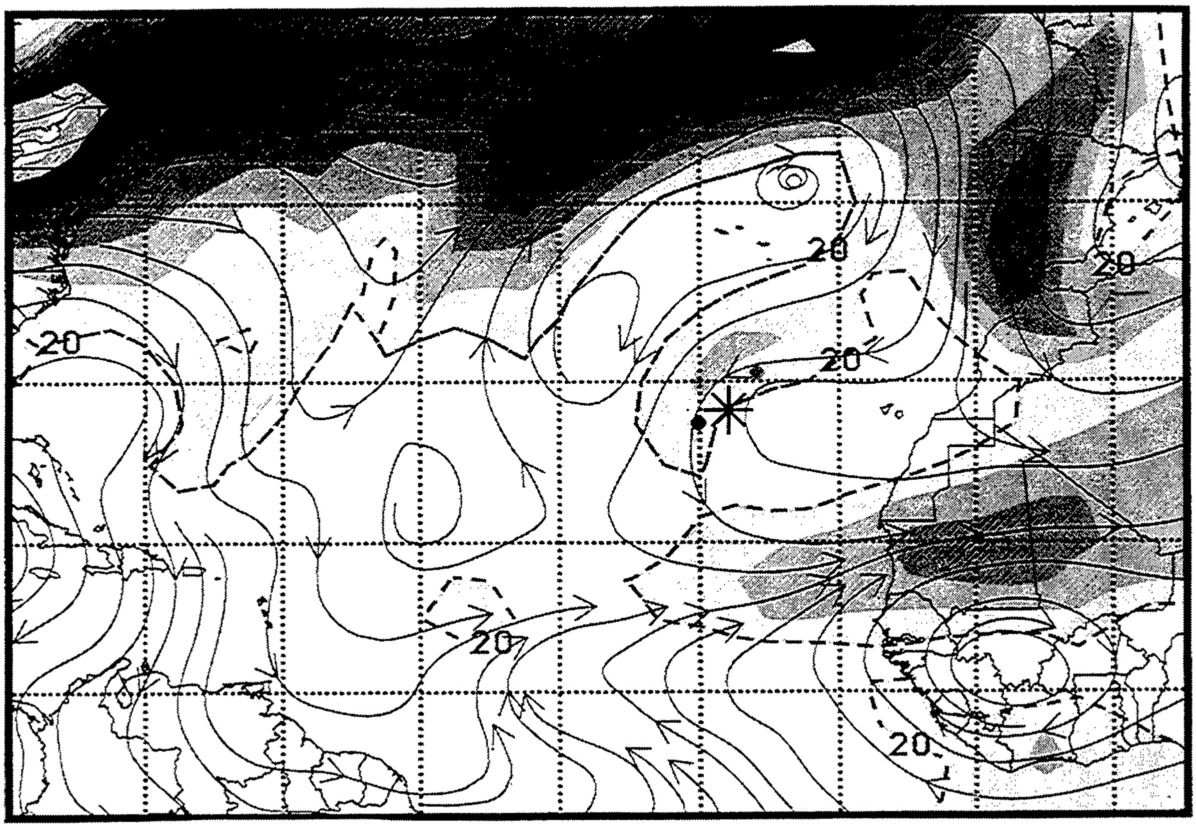


Fig. 11. NOGAPS 500-mb analysis as in Fig. 4, except at 0000 UTC 24 November 1998 for TD Nicole.

3. Tracks. Only 13 TCs during the nine years had periods in the U/PF pattern/region (Fig. 12a) and these represent only 2.6% of the 1568 cases during 1990-1998. These TCs tended to occur in groups, with four (09-12) during 1994, three (06, 07, and 08) during 1996, and two (06 and 08) during 1992. No U/PF tracks were observed in 1993, 1997, and 1998. Many of these tracks originate from 20°N - 30°N where the combination of deep upper-tropospheric lows and sufficiently high sea-surface temperatures exist to sustain a TC circulation. Although most of these U/PF tracks are quite short, two more persistent poleward tracks are also noted. The longest track in the central Atlantic is the Isidore case in Fig. 9b, since Isidore subsequently moved rapidly (15-23 kt) poleward between the strong upper low and an extensive ridge to the east.

The eight TCs that had a period in the U/EF pattern/region also were a mixture of short (transient) and longer (persistent) tracks (Fig. 12b). Since these TCs are between the upper-level trough and the anticyclone to the northwest, they tend to originate farther north (30° - 40°N). As indicated above, these westward tracks are quite anomalous relative to the climatology as few mariners would expect a TC to be approaching from the east at these high latitudes. Perhaps fortunately, TCs in the U/EF pattern/region are rare, with only 1.8% of all cases during 1990-98.

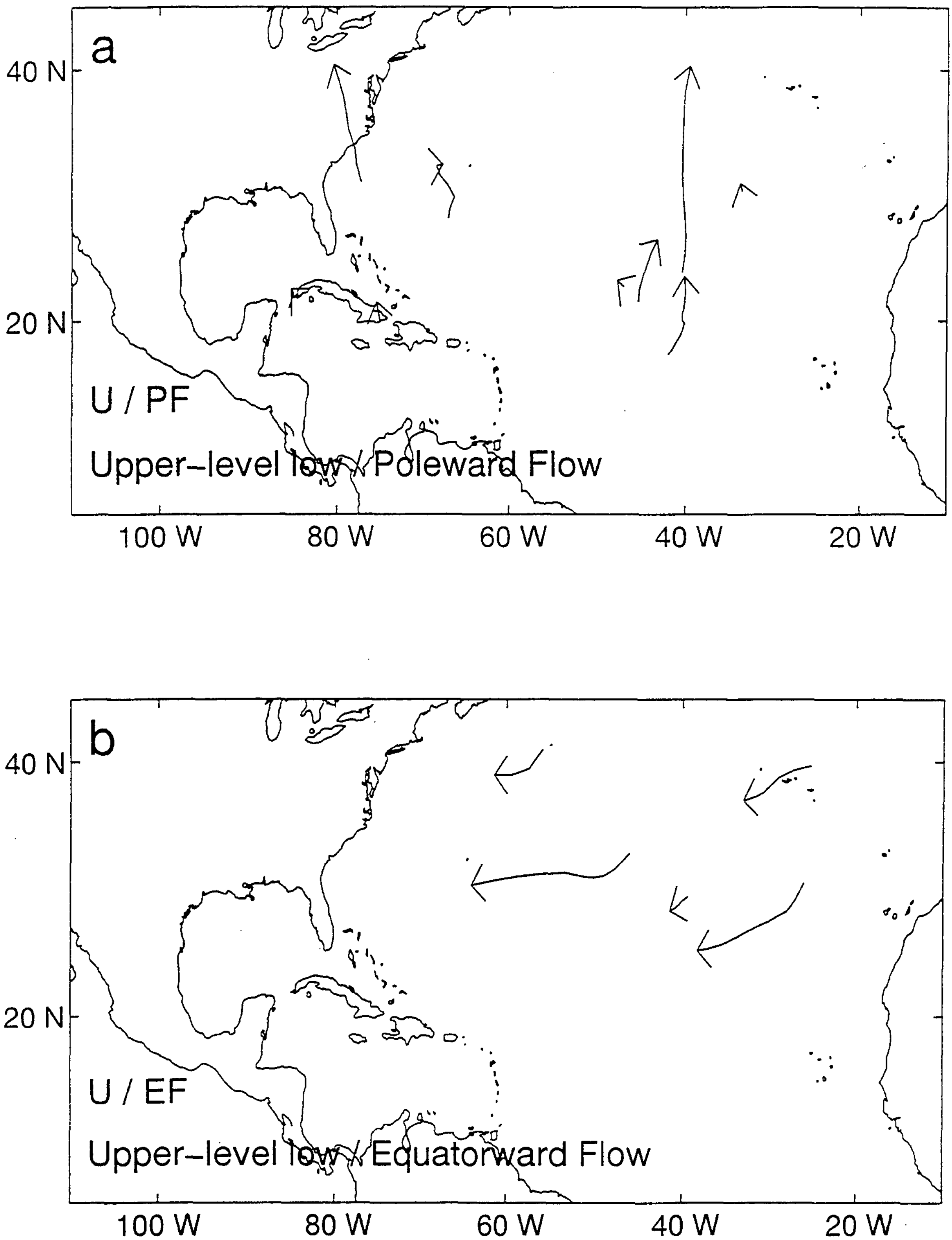


Fig. 12. Track segments as in Fig. 6, except during periods in which the TCs are in the Upper-level (U) low synoptic pattern and the (a) Poleward Flow (PF) and (b) Equatorward Flow (EF) regions.

d. Midlatitude synoptic pattern

1. <u>Conceptual model</u>. The inclusion of the Midlatitude (M) synoptic pattern is another example of a new understanding of the environment structure based on the Atlantic cases in this sample. The original Systematic Approach treatment of western North Pacific TCs that have moved into the midlatitudes was that the TC would be transformed to a baroclinic cyclone while being accelerated into the midlatitude westerlies, or would be dissipated. This reasoning was based on a broader, more stationary subtropical ridge with strong upper-tropospheric westerlies poleward of this ridge in the western North Pacific.

The Atlantic region midlatitude circulations are much more variable in time and in spatial distributions than in the western North Pacific. In addition to the zonal-type subtropical anticyclone in the M pattern conceptual model in Fig. 3 (top), other variations include a more meridional, oval-shaped anticyclone and a triangular circulation with a broad base at southern latitudes and an apex far to the north. Consequently, the Atlantic TC moving poleward along the western flank of the subtropical anticyclone may not be accelerating, especially to the east, as do most western North Pacific TCs. Thus, the M pattern conceptual model includes a Poleward Flow (PF) synoptic region in which the TC may move poleward on the northwestern flank of the subtropical anticyclone sometimes at a more steady translation speed. If a midlatitude trough is present to the north (vice the anticyclone in the conceptual model in Fig. 3), an eastward steering flow will be established over the TC between the midlatitude low and the subtropical high. In this Midlatitude Westerlies (MW) synoptic region, the TC moves eastward with the isotach maximum on the south side. Because these TCs may be sustained over a relatively warm ocean during these eastward tracks, especially over the central latitudes of the Atlantic, the TC may reach the northeastern flank of the subtropical anticyclone and enter a steering flow that has a south-of-east component. In this Equatorward Flow (EF) synoptic region, the isotach maximum will be to the southwest of the TC (Fig. 3).

Another unique M pattern (Fig. 3) feature in the Atlantic is the occasional existence of a separate midlatitude anticyclone poleward of the subtropical anticyclone. Thus, the Midlatitude Easterlies (ME) synoptic region represents a steering flow over the TC that is rarely observed, an Atlantic TC may be translating *westward* in the midlatitudes instead of eastward, and the isotach maximum will be on the north side of the TC.

It is emphasized that the M pattern schematic in Fig. 3 must be regarded as a flexible template that must be adjusted for the wide variety of midlatitude circulation configurations that are observed with the Atlantic TCs. A larger number of M synoptic pattern examples will be presented in the next subsection to illustrate some of this variability.

Another emphasis in this section is the important interactions of the midlatitude trough-ridge circulations with the subtropical circulations that may change the shape and amplitude of the subtropical anticyclone and thus may have an indirect effect on the TC motion. When this interaction leads to an environment structure change for the TC, this Midlatitude System Evolution (MSE) is one of the environment effects included in the transitional mechanisms (Fig. 2, lower left). As illustrated by the schematics in Fig. 13, four options are included in the MSE: Midlatitude Cyclogenesis (MCG), Midlatitude CycloLysis (MCL), Midlatitude

AnticycloGenesis (MAG), and Midlatitude AnticycloLysis (MAL). Each of these is defined as either a superposition effect or an actual amplification (genesis)/decay (lysis) of the midlatitude circulation such that it changes the amplitude, shape, or tilt of the subtropical circulation that is controlling the steering flow of the TC. For example, the zonally-oriented subtropical anticyclone cells in Fig. 13a, which resemble the M synoptic pattern schematic in Fig. 3, might assume a more meridional orientation as in Fig. 13b by amplification of the midlatitude trough-ridge system (actual cyclogenesis) or simply by translation into phase with the subtropical ridge-break-ridge circulation. With a meridional anticyclone pattern, the TC motion on the northwestern (or southwestern) flank of the subtropical anticyclone in the M/PF (or S/PF) pattern/region will have a more meridional motion than with a more zonally oriented subtropical anticyclone, as in Fig. 3.

2. Analysis examples. As indicated above, one Atlantic subtropical anticyclone variant is the more meridional circulation than is shown in Fig. 3. An example is the case of TS Felix (Fig. 14a) that is in the PF synoptic region on the northwestern flank of a meridional subtropical cyclone. In this case, the midlatitude ridge circulation is in phase with the subtropical ridge circulation, which contributes to the meridional amplitude of the subtropical anticyclone. Because the isotach maximum is clearly on the eastern side of Felix, it is clear that it is the meridional anticyclone that is imposing the strong steering flow over Felix. It is also clear that Felix has moved poleward of the subtropical anticyclone axis, but has not advanced into the midlatitude westerlies that are present to the north. Nevertheless, Felix is translating toward 44° and has accelerated from 10 kt to 20 kt over the past 12 h. Thus, the assignment of a M/PF pattern/region is appropriate in this case, and is an example of how the conceptual model in Fig. 3 must be adapted for this meridional configuration.

The example of Hurricane Lili in Fig. 14b is for a late-season storm in which the subtropical anticyclone has been shifted equatorward and is quite zonal west of about 40°W. However, the eastern anticyclone cell extends northeastward to the Iberian Peninsula. Although Lili is embedded in fairly strong southwesterly flow, the isotach maximum to the southeast indicates the primary steering flow over Lili is associated with the tilted subtropical anticyclone branch to the southeast. Since Lili's translation is toward 53° at a speed of 26 kt, the environment structure assignment is in the M/PF pattern/region.

Another late-season, low-latitude TC in the M synoptic pattern is presented in Fig. 15a. Although a series of high-amplitude, midlatitude trough-ridge circulations is found farther north that runs from the midwestern U. S. to Europe, the westerly flow in which TS Grace is embedded is quite zonal. The narrow zonally-oriented subtropical anticyclone cell is displaced equatorward by the encroaching midlatitude westerlies. This case differs from the M pattern schematic in Fig. 3 because of the presence of a trough to the north of the TC. This trough tightens the north-south pressure gradient across the TC, and thus the steering flow in the M/MW pattern/region in the conceptual model (Fig. 3). Although Grace dissipates in the large vertical shear over the next 6 h, the recent translation toward 84° at 28 kt is appropriate for the M/MW classification.

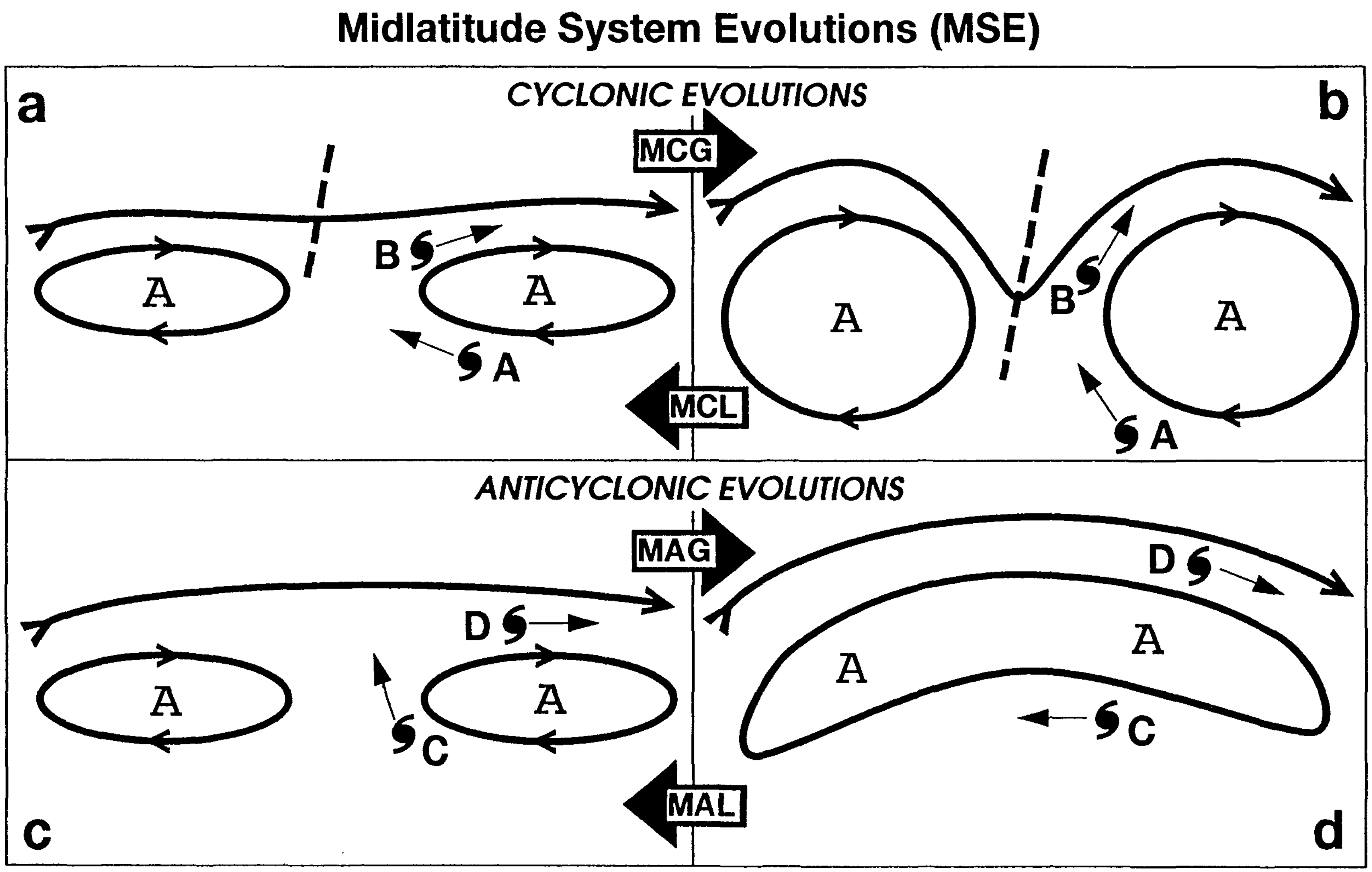


Fig. 13. Schematics of the Midlatitude System Evolutions (MSE) that may affect the TC track. The deepening of the midlatitude trough from panel a to panel b depicts Midlatitude CycloGenesis (MCG) and the reverse order (panel b to panel a) implies Midlatitude CycloLysis (MCL). Similarly, the midlatitude anticyclone change, which typically also results in a subtropical anticyclone change, from panel c to panel d depicts Midlatitude AnticycloGenesis (MAG) and the reverse order (panel d to panel c) implies Midlatitude AnticycloLysis (MAL).

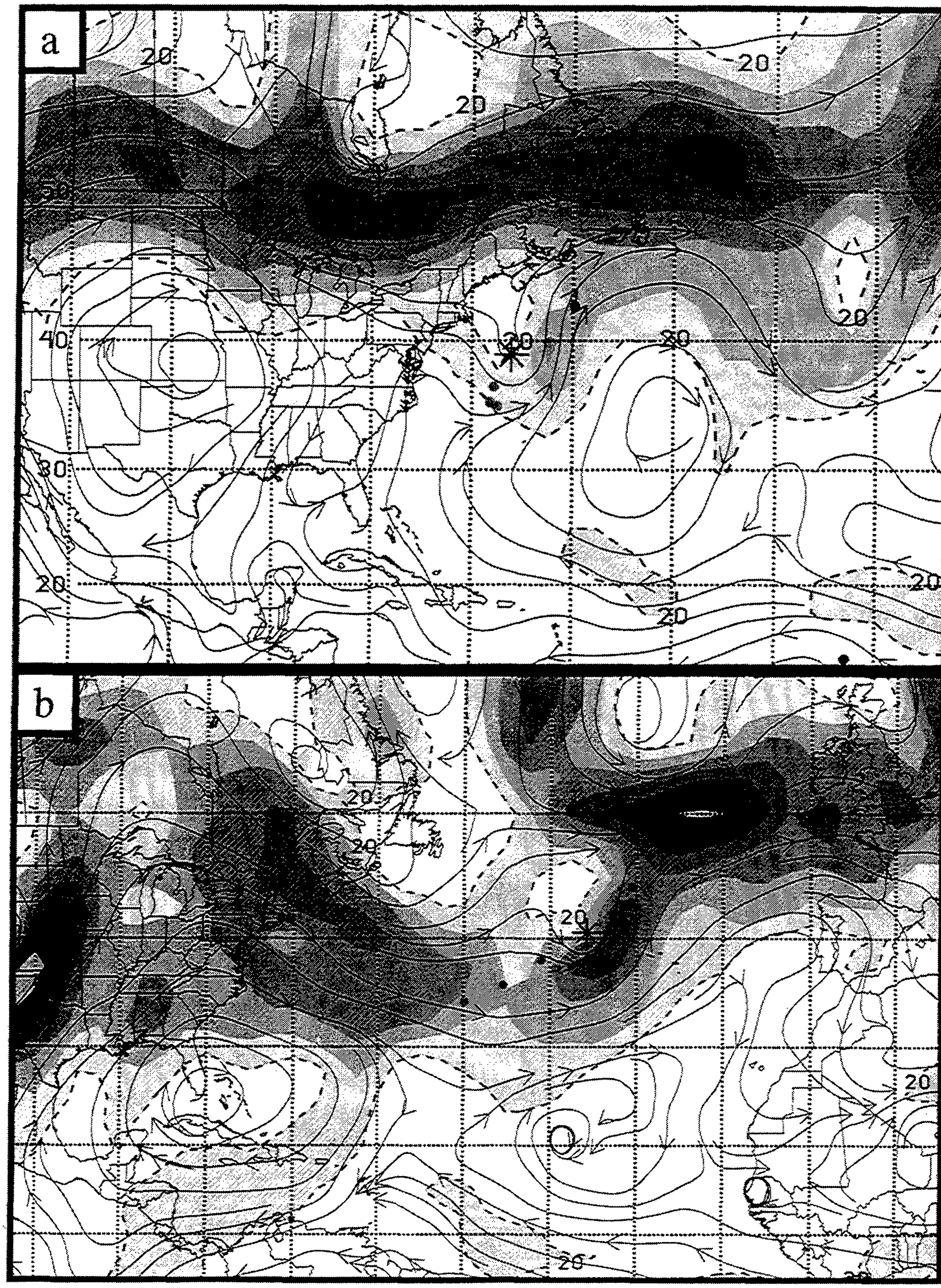


Fig. 14 NOGAPS 500-mb analyses as in Fig. 4, except at (a) 1200 UTC 21 August 1995 for TS Felix, (b) 1200 UTC 26 October 1996 for Hurricane Lili.

An extreme high-latitude example of an Atlantic TC in the M pattern is illustrated in Fig. 15b. TS Josephine formed over the Gulf of Mexico and for awhile was one of the two P/EW tracks in Fig. 9a. After crossing Florida into the Atlantic, Josephine rapidly (about 30 kt) translated toward the northeast in a M/PF pattern. Twelve hours prior to the time in Fig. 15b, Josephine was classified in the M/MW pattern/region, and is now moving toward 86° at 38 kt. This direction and extreme translation speed are consistent with the strong midlatitude westerly steering flow that is evident in Fig. 15b. Even in this strong flow, Josephine is analyzed to have 45 kt winds and will continue to exist another 5 days. This unusual case indicates again how the M pattern conceptual model in Fig. 3 must be adjusted for the extreme variability of the Atlantic midlatitude circulation.

Another late-season situation with highly distorted midlatitude flow is given in Fig. 15c. Notice the deep trough to the west (over Utah) and strong southwesterly flow across the midwest U. S. that turns to westerlies over the Great Lakes, and also the deep trough over the eastern Atlantic. Thus, the subtropical anticyclone is also highly distorted compared to the M pattern conceptual model in Fig. 3, and might have been influenced by another form of MAG than in panels c and d of Fig. 14. TS Gordon is near 31°N, 75°W and drifting southward (toward 179°) at only 6 kt. Since the isotach maximum extends southward on the western side of Gordon, its steering flow is being imposed by the subtropical anticyclone cell to the west-southwest. Taking into account the tilt of this cell, Gordon is in the M/Equatorward Flow (EF) pattern/region of the conceptual model in Fig. 3. The southward (and later westward) track of Gordon is clearly non-climatological, and the forecaster must be aware of the anomalous synoptic conditions leading to such an unusual track. Fortunately, the adjacent data-rich network over the U.S. allows a good depiction of this circulation.

An example that matches the M pattern conceptual model in Fig. 3 is that of TS Nicole in Fig. 15d. Although a 20-kt isotach is not present in the NOGAPS analysis (perhaps owing to a lack of observations), the westward translation would support an isotach maximum to the north of Nicole as in the conceptual model for a M/Midlatitude Easterlies (ME) pattern/region. As described in subsection 3.c.2 above and Fig. 11, Nicole had earlier formed and moved westward in a U/EF pattern/region. Nicole is now moving westward (toward 277°) at 12 kt south of a midlatitude anticyclone cell that is well to the north of a subtropical anticyclone axis that extends southeastward from the Gulf of Mexico to 10°N, 50°W and then eastward to western Africa. Such and equatorial shift of the subtropical anticyclone, and the associated penetration of the midlatitude westerlies so close to the equator, would normally be expected late in the season. Even though this is a very late-season storm, Nicole will intensify to 50 kt in the next 18 h as it is still over a sufficiently warm ocean, and this midlatitude circulation pattern evidently has reduced vertical wind shear to the south of the anticyclone.

These six analysis examples illustrate the variability of the Atlantic midlatitude circulations that may affect the TC track. A flexible application of the M pattern conceptual model provides an explanation for these TC track examples, some of which are quite anomalous. A summary of all of the M pattern tracks is given in the next subsection.

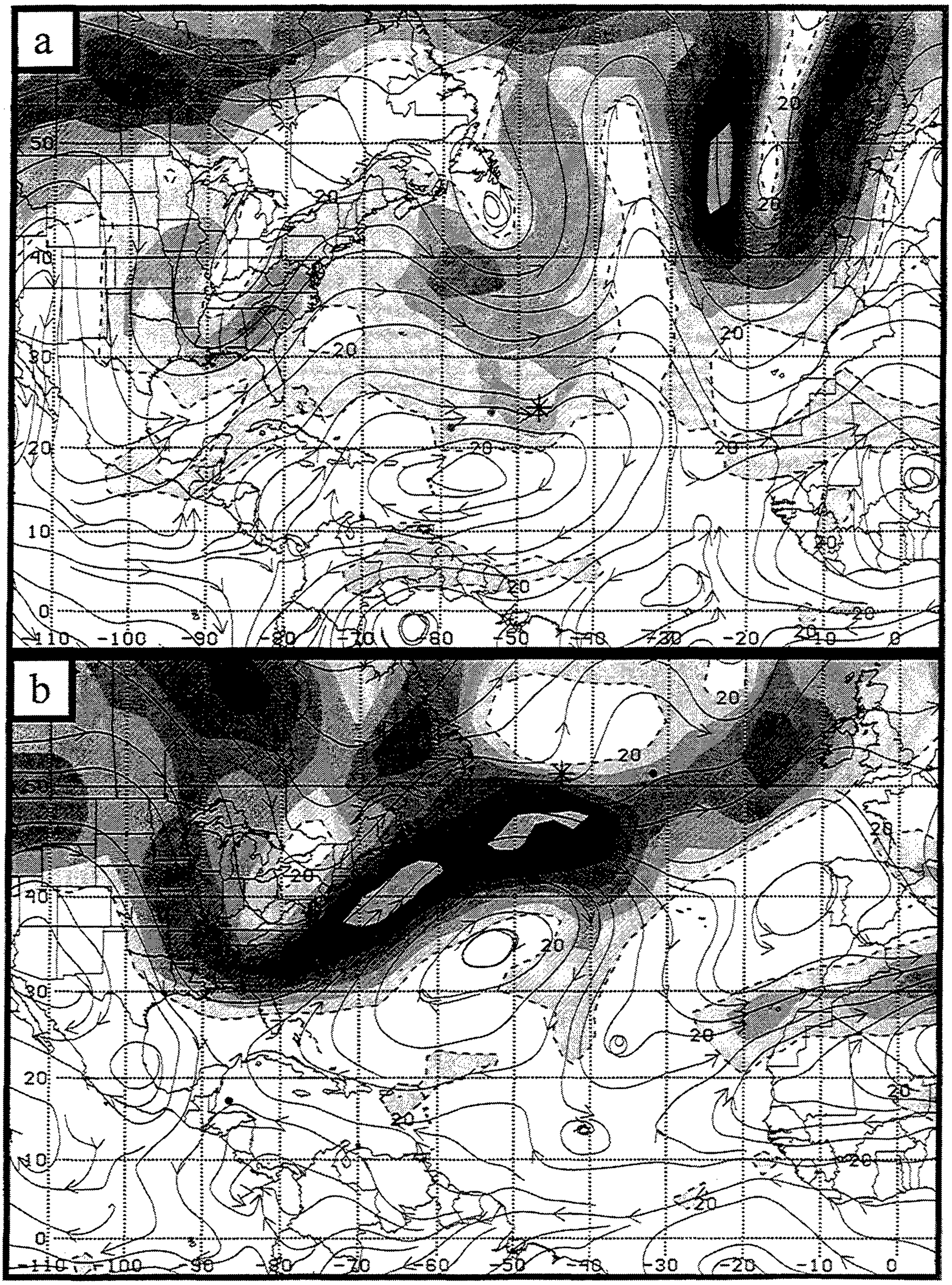


Fig. 15 NOGAPS 500-mb analyses as in Fig. 4, except at (a) 1200 UTC 17 October 1997 for TS Grace, and (b) 0000 UTC 11 October 1996 for TS Josephine.

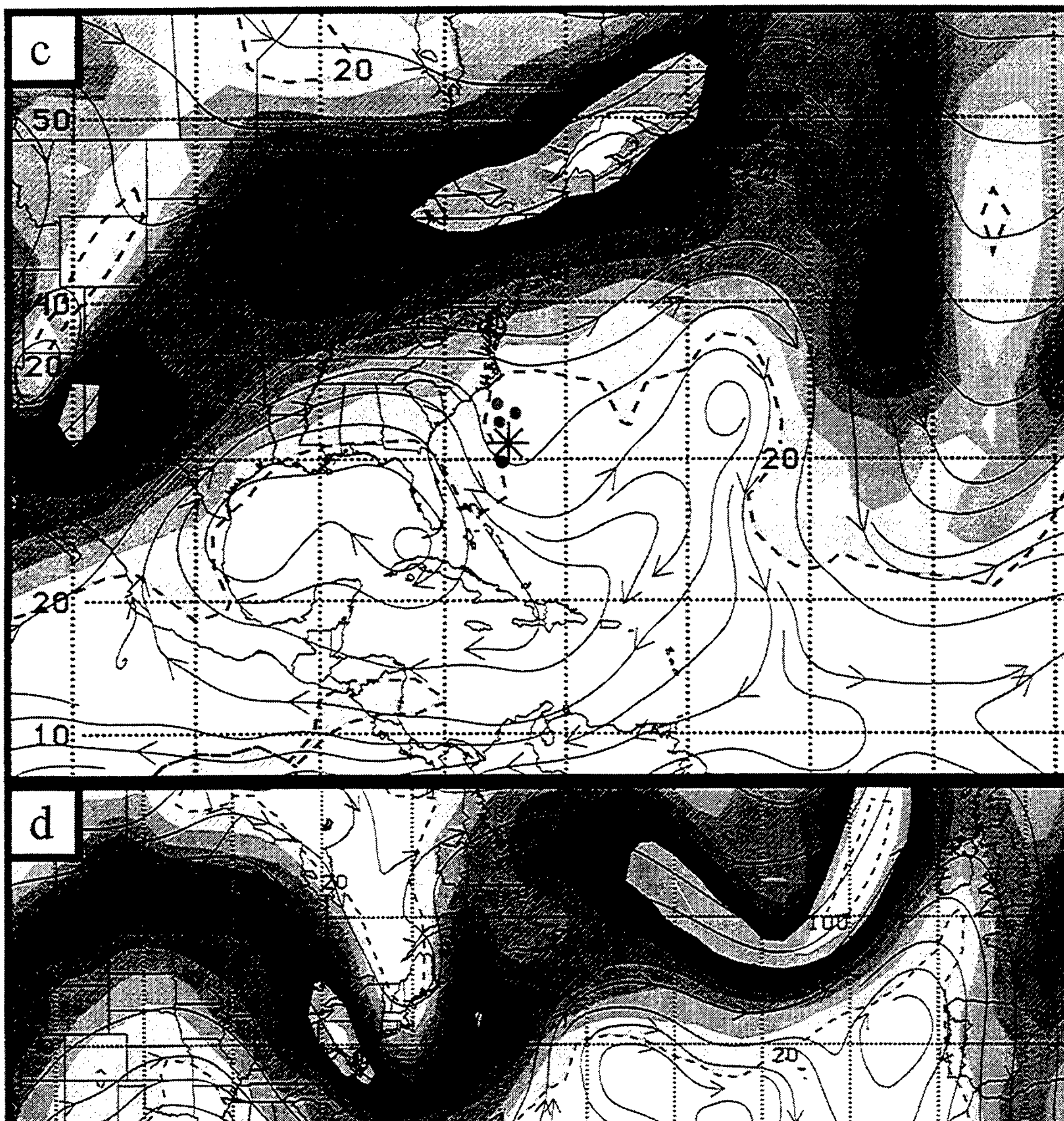


Fig. 15 (continued) NOGAPS 500-mb analyses as in Fig. 4, except at (c) 1200 UTC 19 November 1994 for TS Gordon, and (d) 1200 UTC 27 November 1998 for TS Nicole.

3. Tracks. A total of 17.3% of the 1568 cases during 1990-1998 were in the M/PF category. As depicted in the M pattern conceptual model in Fig. 3, the M/PF tracks (Fig. 16a) are characteristically toward the northeast. However, some of these tracks have a cyclonic turn toward the north (or even northwest) late in the life cycle, as the TC remnants move into a reverse-tilted (northwest-southeast) midlatitude trough/ridge pattern. Although many of the M/PF tracks are relatively short, which indicates a transition to another pattern/region (e.g., M/MW) or possibly dissipation, other tracks are surprisingly long. In part, the long tracks may arise from the NHC practice of maintaining the systems as long as they have some tropical characteristics and pose a danger to maritime activities in the North Atlantic. However, recent studies of extratropical transition (Browning *et al.* 1998; Thorncroft and Jones 1999) have indicated that some Atlantic hurricanes can continue well to the east, perhaps in conjunction with the warm waters of the Gulf Stream extension.

Such long eastward tracks are even more evident in the M/MW pattern/region (Fig. 16b). As expected from the definitions of synoptic regions in the M conceptual model, these MW tracks are more eastward than in the PF region. These MW tracks span a wide range of latitudes from 20°N to 50°N, which again emphasizes the variability of the Atlantic midlatitude circulations that may affect TC tracks. Some of the variability was illustrated in the case studies of Grace (Fig. 15a), Josephine (Fig. 15b), and Nicole (Fig. 15d). The M/MW cases account for 12.1% of the sample.

The M/EF cases only represent 3.6% of the 1568 cases. The M/EF tracks (Fig. 16c) are generally quite short. The short tracks suggest that the synoptic conditions are transient. Even though such tracks are rare, the anomalous southward tracks are very non-climatological. Clearly, the forecaster must be alert to the synoptic conditions that lead to such anomalous tracks, and be able to forecast how long these conditions will persist.

The M/ME cases are even more rare, with only 1.2% of the sample. Again, the M/ME tracks (Fig. 16d) are generally short, although one case off the east coast of the U. S. is surprisingly long. Since the M/ME cases exist in conjunction with a midlatitude anticyclone north of the subtropical anticyclone axis, they are necessarily found relatively far north. These cases will be favored in the late season when the subtropical ridge is displaced equatorward and yet the sea-surface temperatures are high enough to sustain a TC south of a midlatitude anticyclone. As in the M/EF cases, these M/ME tracks are highly non-climatological, and thus represent a challenging forecast situation for the TC forecaster.

e. *Environment structure summary*

A summary of the environment structure classifications for the 1568 cases during 1990-98 is given in Fig. 17. The sample includes 114 TCs during this period, with a variation from only eight during 1997 to 21 during 1995. Consequently, the number of 12-h cases classified in each year ranged from only 89 during 1997 to 350 during 1995.

The Standard (S) pattern includes 47.9% of the total sample, with 30.5% of all cases in the S/Tropical Easterlies (TE) pattern/region (Fig. 17). As indicated in Fig. 6a, these are predominantly the long westward tracks from near Africa to the Caribbean and Gulf of Mexico.

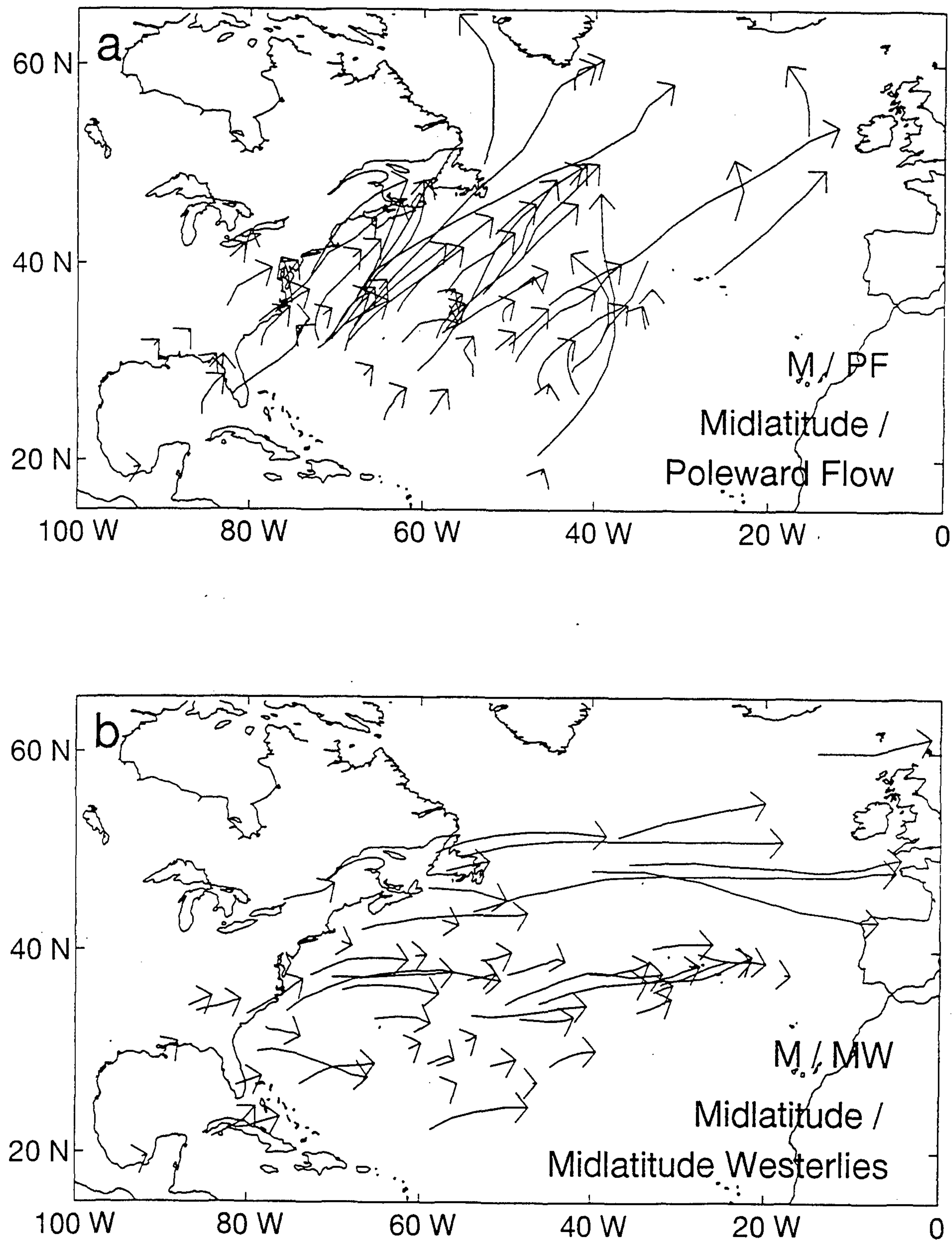
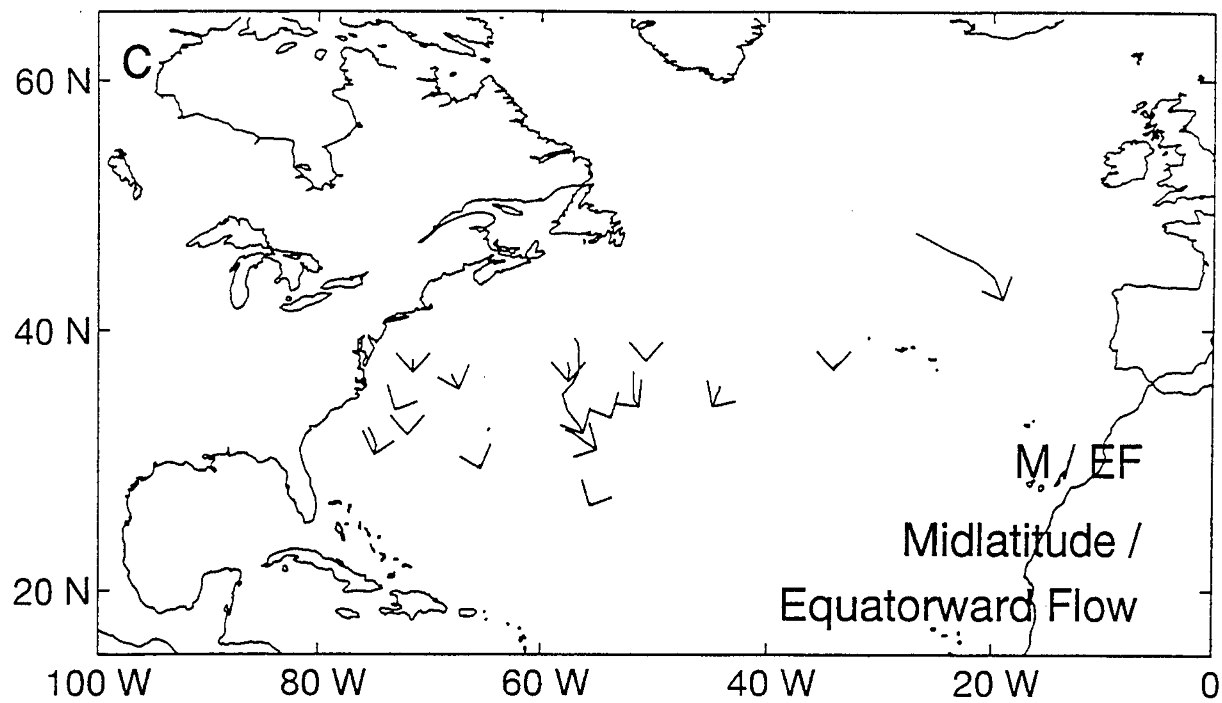


Fig. 16. Track segments as in Fig. 6, except for the Midlatitude (M) synoptic pattern and the (a) Poleward Flow (PF), and (b) Midlatitude Westerlies (MW) regions.



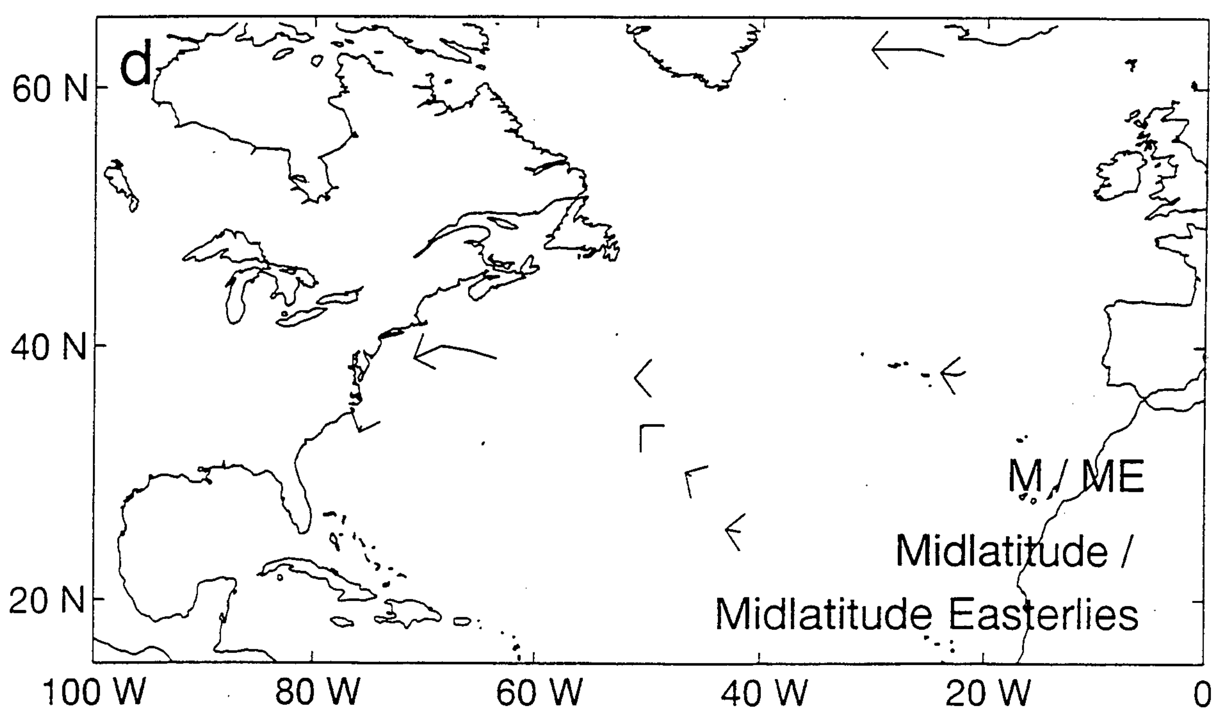


Fig. 16. (continued) Track segments in the M pattern and (c) Equatorward Flow (EF), and (d) Midlatitude Easterlies (ME) regions.

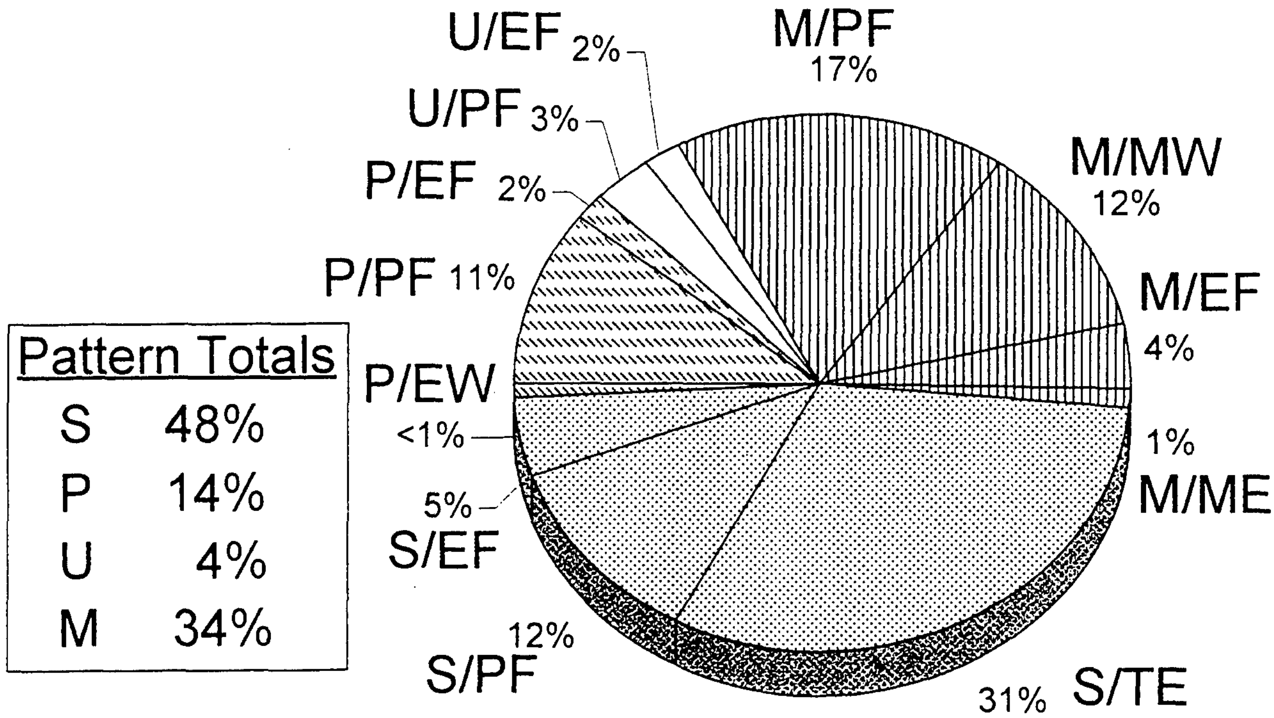


Fig. 17. Frequency distribution of pattern/region classifications for Atlantic TCs during 1990-98. See Fig. 3 or Fig. 18 for definitions of the pattern/regions.

Given the steady westward tracks of many of the S/TE tracks, it might be expected that a Climatology-Persistence (CLIPER) track prediction technique would be effective in this pattern/region. With the relatively frequent meridional subtropical anticyclones in the Atlantic, the TC may remain in the S/ Poleward Flow (PF) pattern/region (see Fig. 6b) for some time, and TCs in S/PF constitute 12.6% of all cases. The TCs that have an Equatorward Flow (EF) steering component in the S pattern tend to be transient with short track segments (see Fig. 6c), so that only 4.8% of all cases are in the S/EF pattern/region (Fig. 17). These anomalous equatorward and transient tracks in the S/EF pattern/region would not be predicted well with the CLIPER technique. As listed in the annual summaries in the Appendix, two years (1992 and 1997) had no track segments in the S/EF pattern/region. However, 9% of the cases during the busy 1995 season were in the S/EF pattern/region. This variability in the number of easier or more difficult track prediction scenarios may contribute to year-to-year variations in forecast accuracy.

Another extremely rare environment structure in the Atlantic is the Poleward/Equatorial Westerlies (P/EW) pattern/region, which occurred only during 1997 and 1998 and constituted only 0.6% of the 1568 cases (Fig. 17). The PF region is the most common of the regions in the P pattern, with 11.2% of all cases. As illustrated by the P/PF tracks in Fig. 9b, the special character of this environment structure is an "early" poleward turn in an area that climatologically might be expected to have westward steering flow. Given the relatively frequent P/PF occurrences and the anomalous tracks (not expected to be predicted well by CLIPER), the forecaster needs to be alert to the presence or development of a peripheral anticyclone to the east and southeast of a TC (Fig. 3). When such conditions exist, the forecaster should also expect the development of another TC in the downstream cyclonic region of the Rossby wave train of the western TC. The eastern TC may then be in the P/EF pattern/region (Fig. 3), and would be expected to have an equatorward component of steering in conjunction with the peripheral anticyclone of the western TC (or perhaps a midlatitude cyclone during the late season). As indicated in Fig. 17, these TCs in the P/EF pattern/region are relatively rare, with only 1.7% of all cases.

The Upper-level (U) low synoptic pattern is a special circulation of the Atlantic that determined the tracks of 4.4% of the 1568 cases during 1990-98 (Fig. 17). As in the P/PF tracks, the forecaster must be alert to the unusual condition of a downward extension of the upper-level low that creates a poleward steering in the U/PF pattern/region. Whereas the U/PF cases are rarely observed (2.6%), the associated tracks (see Fig. 12a) are quite anomalous, especially the few persistent poleward tracks. The formation of Atlantic TCs in the U/EF pattern/region is also of special note because they occur at relatively high latitudes. As indicated in Fig. 12b, some of these tracks are surprisingly long, which indicates that the synoptic conditions persist for some time. Although only eight TCs were found in the 1990-98 sample to be in the U/EF pattern/region, they constitute 1.8% of the 1568 cases.

One of the defining characteristics of Atlantic TC track forecasting is the importance of the Midlatitude (M) synoptic patterns. More than one third (34.2%) of all the 1990-98 cases are in the M pattern (Fig. 17). As illustrated by the examples in section 3.d.2, the idealized M pattern schematic in Fig. 3 must cover a large variety of actual midlatitude circulation configurations, amplitudes, and tilts. The second-most common of all pattern/regions is the M/PF with 17.3% of all cases. As indicated by the tracks in Fig. 16a, these TCs constitute a major threat to Atlantic maritime shipping. Although primarily northeastward, some tracks also have a cyclonic curvature later in the life cycle. Similarly, the frequently occurring (12.1%) M/Midlatitude Westerlies (MW) tracks (Fig. 16b) are also a major threat to the primary shipping routes between the U.S. and Europe and Africa. Indeed, some of these M/MW tracks extend to Europe, perhaps because the Gulfstream extension continued to provide a warm ocean environment to sustain a TC-like circulation.

A related special characteristic of Atlantic TC forecasting is that systems may be sustained as they move to the northeastern flank of the subtropical anticyclone cell such that the TC then experiences an equatorward steering component in the M/EF pattern/region. Although relatively rare with only 3.6% of the 1568 cases (Fig. 17), these M/EF tracks (see Fig. 16c) are anomalous relative to the more common M/PF (Fig. 16a) and M/MW (Fig. 16b) tracks. The most unusual synoptic scenario of the M pattern is the Midlatitude Easterlies (ME) region (Fig. 3), with the TC being poleward of a (low-latitude) subtropical anticyclone and yet be equatorward of a midlatitude anticyclone. Thus, a westward steering flow is over the TC, which is then moving westward (Fig. 16d). As these synoptic conditions are transient, the M/ME tracks (Fig. 16d) are generally (with one notable exception) short, and only 1.2% of all the 1990-98 cases were in the M/ME pattern/region (Fig. 17).

In summary, about half of all Atlantic TCs are in the S pattern. At least the 43.1% cases in the S/TE and S/PF pattern/region resemble the common track along the equatorward and southwestern flanks of the Atlantic subtropical anticyclone that leads to recurvature. However, more than one third of the Atlantic TC track forecasts are actually initiated poleward of the subtropical anticyclone axis. In addition to some 17.3% with tracks toward the northeast, another 12.1% have tracks toward the east and some extend to Europe! A relatively large number of the Atlantic TC track forecast scenarios depart from this predominant climatological westward-poleward-eastward track. Considering the S/EF (4.8%), all of the P pattern variations (13.5%), and the U pattern (4.4%), nearly one quarter of all Atlantic scenarios that are still equatorward of the subtropical anticyclone axis may be considered to have non-climatological tracks. Adding in the very anomalous M/EF (3.6%) and M/ME (1.2%) tracks poleward of subtropical anticyclone axis, nearly 30% of all Atlantic track forecasting situations are non-climatological. The surprising variety of Atlantic TC track scenarios is illustrated well by the distribution of environment structure classifications in Fig. 17.

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4. ENVIRONMENT STRUCTURE TRANSITIONS

As illustrated in the synoptic pattern/region conceptual models in Fig. 3 (repeated for convenience in Fig. 18) and the corresponding pattern/region tracks in Figs. 6, 8, 12, and 16, as long as a TC remains in the steering flow associated with a particular pattern/region, the TC motion will tend to fall within a certain range of directions and speeds, i.e., in a characteristic track. It is possible for a TC to remain in the same pattern/region combination throughout its existence, with the most common case being "straight-running" TCs that remain in the tradewind easterlies equatorward of the subtropical anticyclone, which is the S/TE pattern/region (Fig. 18). However, most of the TCs in the Atlantic basin follow more complex tracks owing to changes in the environment structure in the vicinity of the TC. In the Systematic Approach Meteorological knowledge base (Fig. 2), these changes are "transitions" from one pattern/region combination to another. Mechanisms that act to change the TC-environment structure are called transitional mechanisms (Fig. 2, bottom). The recognition and prediction of the timing of the completion of the transition is important to the forecaster because it involves a track change. Some examples of these transitional mechanisms have already been presented above: SCI in Fig. 5a-b; ICI in Fig. 5c-d; DCI in Fig. 10; and MSE in Fig.13. Other transitional mechanisms in Fig. 2 will be introduced below and a summary of all of the conceptual models and examples in this report will be given later in Table 2 in section 5.

An overview of the most frequently occurring environment structure transitions and associated transitional mechanisms during the period of this study is presented in this section. A series of mini-case studies with NHC tracks and NOGAPS analyses are used to illustrate some of these frequently occurring transitions.

a. Frequency of occurrence

In this sample of 114 TCs during 1990-98, a total of 258 environment structure transitions (i.e., synoptic pattern/region changes) occurred (Fig. 19). However, 47 of these transitions between two pattern/region combinations occurred fewer than four times; on average once in three years. Thus, only the 211 transitions that involved transitions between pattern/regions occurring four or more times are displayed in Fig. 19. Because some of the 114 TCs had no (or only one) transitions, the forecaster can expect many of the remaining Atlantic TCs to undergo three or more transitions (or track changes) during the TC life cycle.

Focusing first on the most common transitions in Fig. 19, the classical recurvature track is evident in the 26 transitions from the S/TE to the S/PF combination, the 20 transitions to the M/PF pattern/region, and then the 30 transitions to the M/MW combination. An alternate poleward track segment from the westward track in S/TE is the 21 transitions to the P/PF combination and then the 17 transitions to the M/PF pattern/region. As indicated in section 3b, the key circulation in the P/PF conceptual model is the peripheral anticyclone to the southeast of the TC that establishes a poleward steering component. By contrast, the S/TE to S/PF transition involves the advection of the TC from equatorward side of the subtropical anticyclone to the southwest flank. Whereas the S/TE to S/PF transition (and track change) is more gradual, the change to a more poleward track in the P/PF pattern/region may result in a sharper turn.

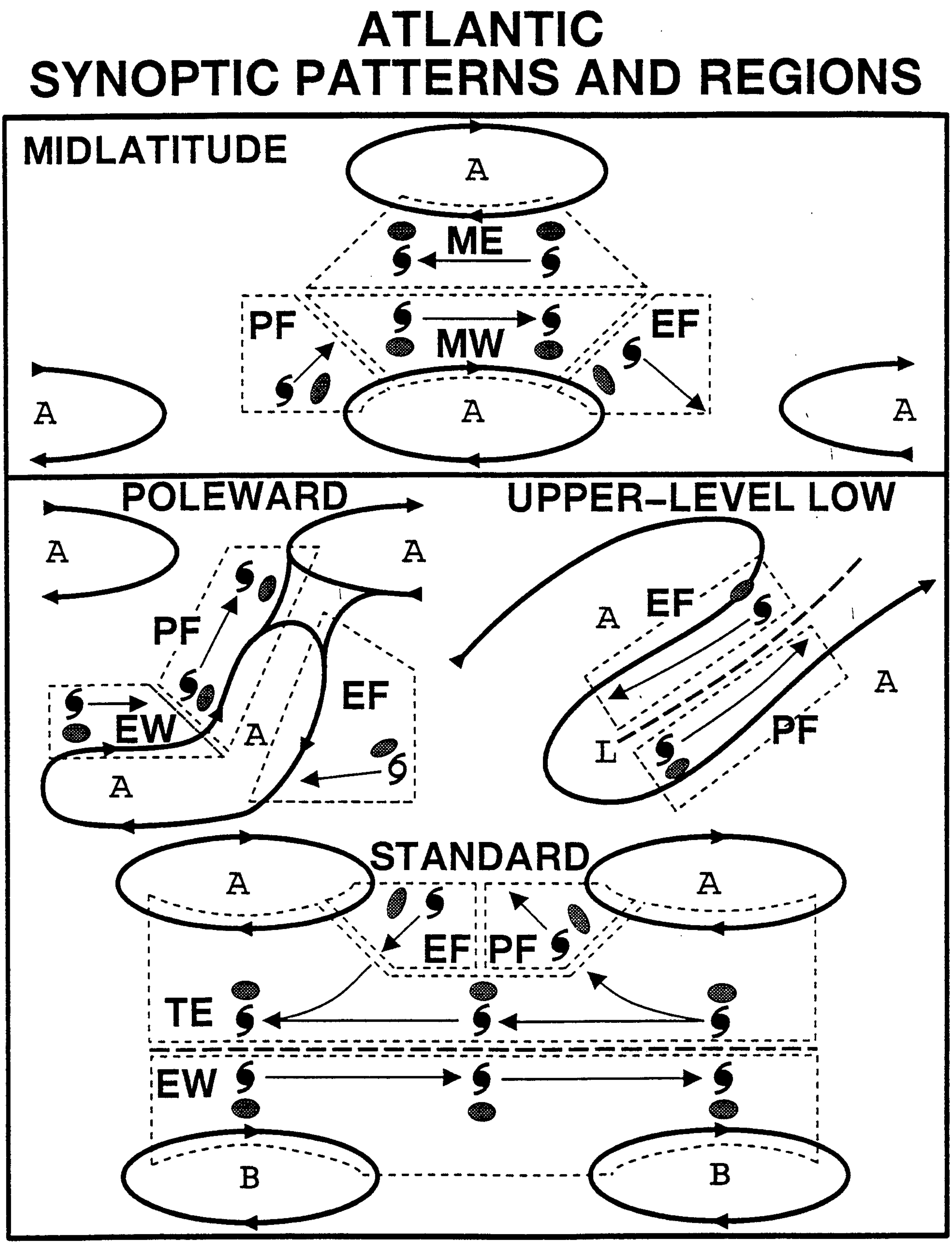

Fig. 18. Atlantic synoptic pattern/region combinations repeated from Fig. 3 to facilitate interpretation of Fig. 19.

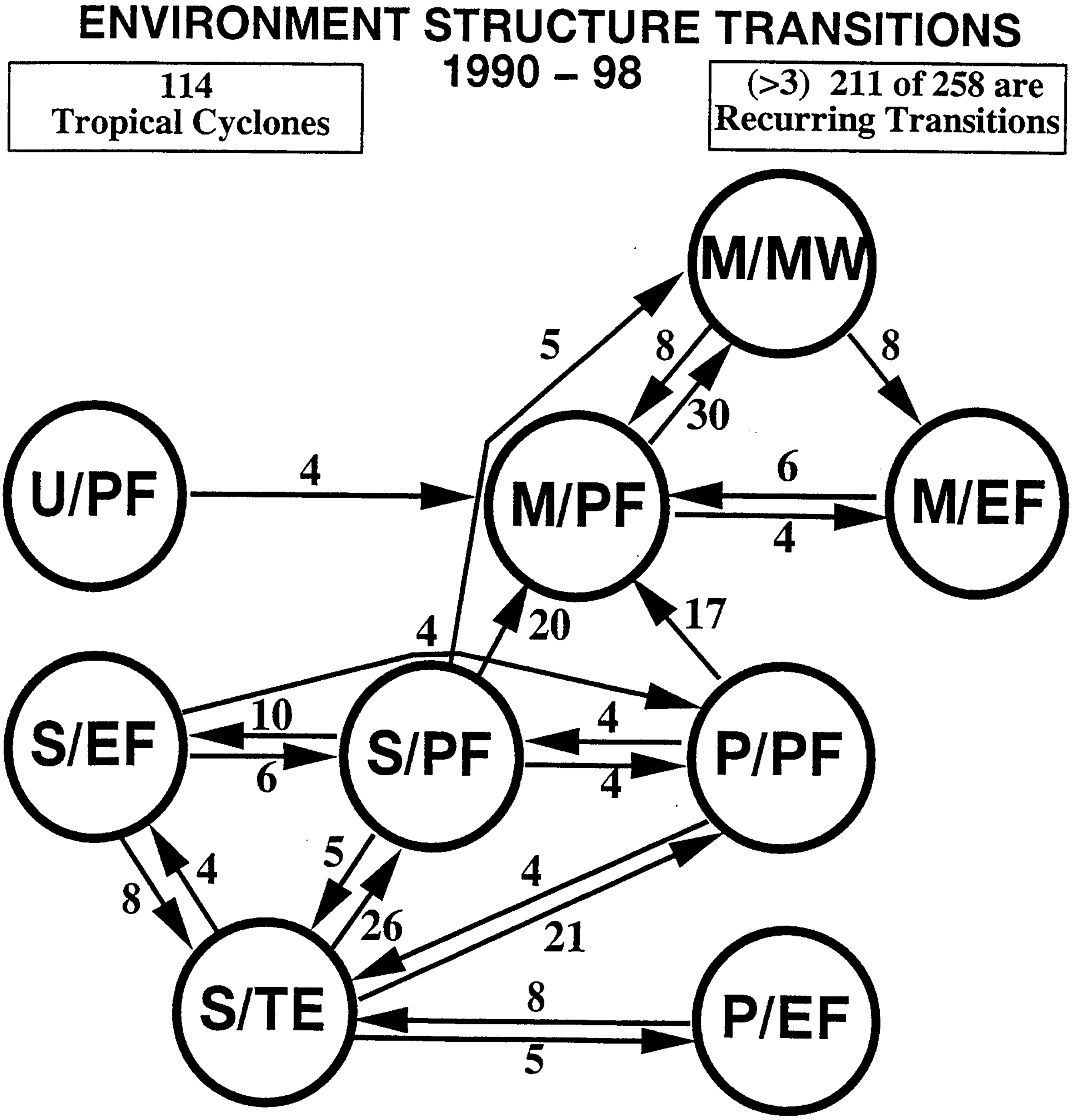

Fig. 19. Environment structure transition occurrences for 114 TCs in the Atlantic during 1990-98, where the synoptic pattern/region combinations are illustrated in Fig. 18. Only "recurring" transitions that occurred four or more times during the period are included, which represents 211 of the 258 total transition occurrences.

The complexity of the transition diagram in Fig. 19, even including only those transitions that occurred four or more times, simply reflects the complexity of Atlantic TC track forecasting. Notice that nearly all of these transitions between synoptic pattern/region combinations in Fig. 19 are actually two-way. Thus, a transitional mechanism acting for a limited time may lead to pattern/region change. However, termination of that mechanism may cause the TC motion to revert to the prior environmental steering flow, so that TC track would have had a temporary track deflection before resuming the prior track orientation. This would be recorded in Fig. 19 as two transitions--one in each direction between the two-pattern/region combinations.

It is also helpful to remember that a TC can only be in one pattern/region at any time. Thus, the attention of the forecaster should be on what transitional mechanisms might be present that will cause the environment structure to change--otherwise the TC motion will continue under the present environmental steering and continue along the characteristic track for that synoptic pattern/region. The transition diagram in Fig. 19 can assist the forecaster in assessing the likelihood of a transition to some other pattern/region. In the simple case of a TC in the U/PF pattern/region, only a transition to the M/PF pattern/region occurred at least four times during the nine-year period. That is, the forecaster can reasonably expect a TC in the U/PF pattern/region to recurve through the subtropical anticyclone axis into the midlatitudes with a continued poleward steering flow. The options for a TC in the most common (see Fig. 6a) S/TE pattern/region are more numerous. However, the two most-frequent transitions *from* the S/TE pattern/region are the 26 to the S/PF and the 21 to the P/PF combinations, which are both to more poleward tracks. Less frequently, the TC may leave the S/TE pattern/region to the P/EF and S/EF combinations, which represents an equatorward turn in the track. Thus, the relative frequencies of transitions from a specific pattern/region in Fig. 19 indicate the likelihood of different TC track changes, and the above example of the transitions from the S/TE pattern/ region indicates a poleward track change is more likely than an equatorward turn by a 47:9 ratio.

Similarly, the inbound arrows in Fig. 19 indicate the transitions by which a TC might enter a particular synoptic pattern/region. For example, the most likely transitions *to* the S/TE pattern/region are from the P/EF and S/EF combinations, i.e., a situation of a TC with an equatorward steering component is likely to turn toward a westward steering flow in the S/TE pattern/region. Less frequently, a TC moving poleward in either the S/PF or P/PF combinations may turn to a westward track (so-called stairstep track) in the S/TE pattern/region. This transition could occur because the circulation feature causing poleward motion weakens or the subtropical anticyclone to the west may build eastward, perhaps in conjunction with the passage of a midlatitude ridge (Fig. 14c-d), such that the TC again enters the S/TE pattern/region. Notice in Fig. 19 that a relatively frequent (10 cases) transition from S/PF is to the S/EF pattern/region, which would be a stairstep track tilted equatorward of west after having previously been moving poleward.

The following mini-case studies provide examples of some of these transitions by illustrating the track changes and the evolution of the synoptic circulations that accompany these environment structure transitions. As indicated above, once the forecaster has established which pattern/region the TC is presently in, the focus should be on which synoptic transitions may be in progress that could lead to a departure from a persistence (of past motion) track, and when that track change will occur. In these case studies, the reader has the benefit of hindsight. In real-time, the forecaster needs accurate and timely guidance that these environment structure changes are going to occur.

b. Transition Examples

1. TC Bonnie (S/TE → S/PF → M/PF). The case of Bonnie during 1998 is an example of a "classical recurvature" track in the sense of a parabolic shape of westward to poleward to eastward motion, except that variability in the adjacent circulations led to important accelerations and decelerations. TC Bonnie at 0000 UTC 26 August 1998 was shown in Fig. 4b as an example of the Standard (S)/Poleward Flow (PF) pattern/region. In this section, the transitions from the preceding S/Tropical Easterlies (S/TE) to the S/PF and then to the M/PF pattern/region will be described. The track of Bonnie during this period is given in Fig. 20. Whereas Bonnie on around 1200 UTC 20 August had been translating westward (heading ~ 285°) at about 25 kt, Bonnie decelerated on 23 August to around 5 kt while northeast of the Bahamas. After being nearly stalled for almost two days, Bonnie then resumed a northwestward track at a typical translation speed of about 12 kt. However, Bonnie again slowed to about 5 kt on 27 August while over eastern Virginia. After about 36 h, Bonnie moved northeastward over the Atlantic and was moving at 30 kt on 30 August. These accelerations and decelerations along the classical recurvature track are clearly of great importance in predicting the timing of warnings for coastal regions and maritime activities. Both of the near stalls in translation occurred in conjunction with environment structure transitions.

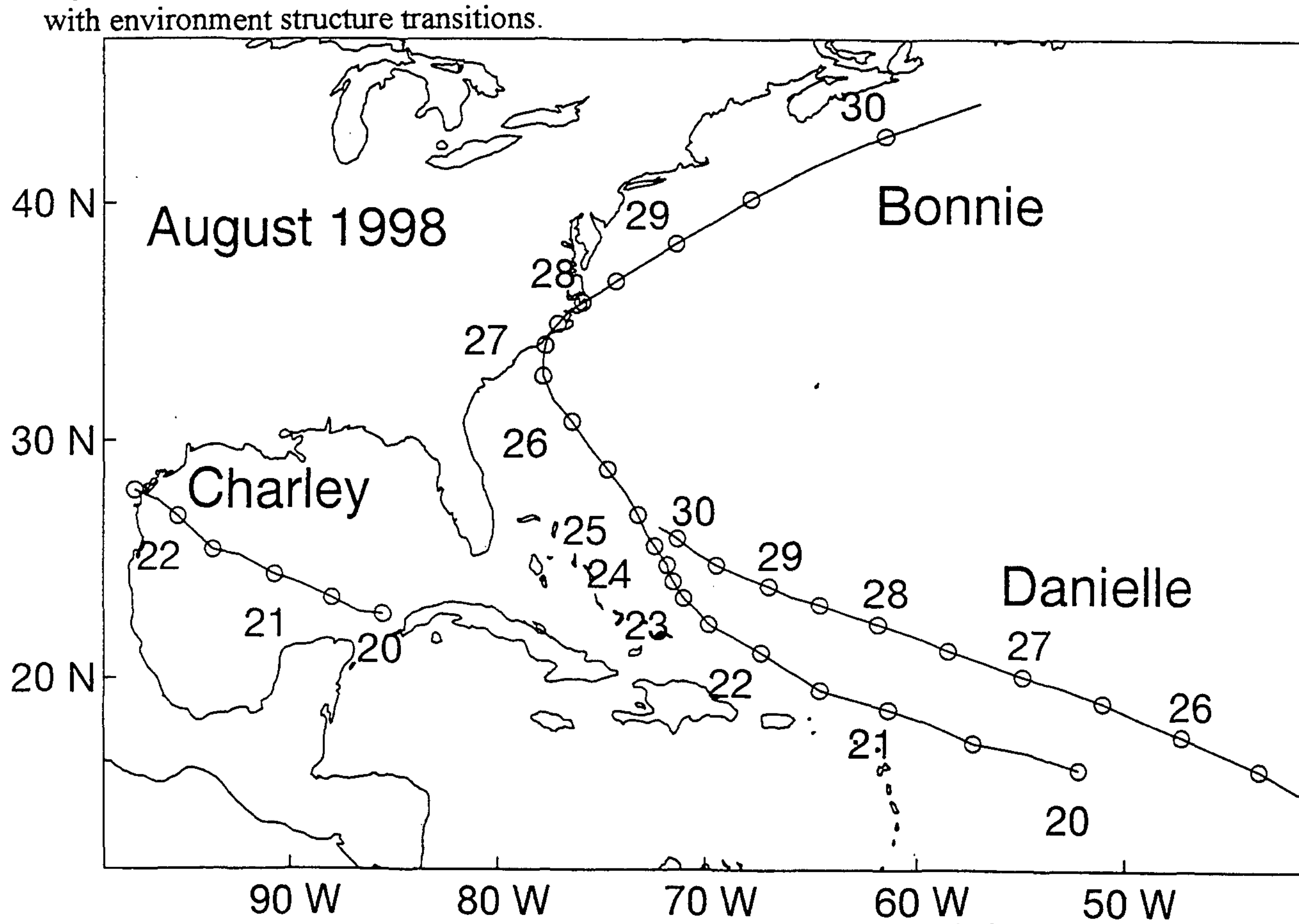

Fig. 20. Tracks of TCs Bonnie, Charley, and Danielle during 20-30 August 1998. Open dots along the track are each 12 h and the open dot with number is the 0000 UTC position.

At 1200 UTC 21 August (Fig. 21a), Bonnie is northeast of Puerto Rico and is moving toward 293° at 15 kt. Bonnie is equatorward of a northwest-to-southeast tilted subtropical anticyclone axis. The isotach maximum is slightly east of north, so that Bonnie is clearly in a S/TE pattern/region (Fig. 18). Notice that a midlatitude trough has established a break between two subtropical anticyclone cells: one centered near 29°N, 54°W and the other over the eastern central U.S. Although the trough has penetrated to about 30°N, it is not directly affecting the track of Bonnie at this time, since Bonnie is well south of this break.

TC Charley, which is near 25°N, 94°W at this time, has now developed to Tropical Storm (TS) intensity over the warm waters of the Gulf of Mexico. Charley, which with Bonnie is clearly a part of a sequence of westward-moving waves equatorward of the subtropical anticyclone, is in the S/TE pattern/region. Given the meridional and zonal extent of the western subtropical anticyclone circulation, a continued westward track into Texas is expected.

By 1200 UTC 22 August (Fig. 21b), Bonnie has turned to a heading of 305° and has slowed to 10 kt. The eastward translation of the midlatitude trough over the past 24 h has shifted southward the eastern subtropical anticyclone circulation, which is now near 24°N, 60°W. This eastern anticyclone is exerting a more poleward steering component over Bonnie, which is reflected by a shift of the isotach maximum to the northeast of Bonnie. Since Bonnie is now approaching the southwestern flank of the (tilted) subtropical anticyclone, Bonnie is considered to be in a transitional state toward the S/PF pattern/region (Fig. 18). The translational deceleration from 15 kt to 10 kt over the past 24 h is another indication that the environmental steering is in the process of changing. Since it was the translation of the midlatitude trough that led to the shift in the eastern subtropical anticyclone, the MCG transitional mechanism in fig. 14a-b is considered to be contributing to the transition.

TC Charley has moved onto the Texas coast and is dissipating. It has remained in the S/TE pattern/region throughout its short life cycle, since it has been equatorward of a strong and broad subtropical anticyclone. Thus, its environmental steering has not been affected by any adjacent circulation changes.

By 1200 UTC 23 August (Fig. 21c), the translation speed of Bonnie has slowed to 4 kt with a heading toward 238°. Bonnie has approached the large break region between the subtropical anticyclone over the eastern U.S. and the anticyclonic cell to the east of Bonnie, which has been greatly weakened over the past 48 h by the passage of the midlatitude trough (compare with Fig. 21a). Consequently, the steering flow over Bonnie is very weak, and Bonnie slowly drifts northwestward over the next two days (Fig. 20). Thus, Bonnie is the S/PF pattern/region and is expected to remain in this region for some time as it is still some distance from the subtropical anticyclone axis, and it is moving slowly.

Two and one half days later (Fig. 21d), Bonnie is moving toward 322° at 12 kt and is clearly threatening the east coast of the U. S. The increased translation speed is in response to a much stronger subtropical anticyclone cell to the east of Bonnie, which is reflected by the 40-kt isotach maximum on the east side. However, the subtropical anticyclone to the west over the U. S. is also quite strong, which is indicated by the 30-kt isotach maximum to the west. Thus, Bonnie is moving into a narrow break region between two strong anticyclonic cells. Since

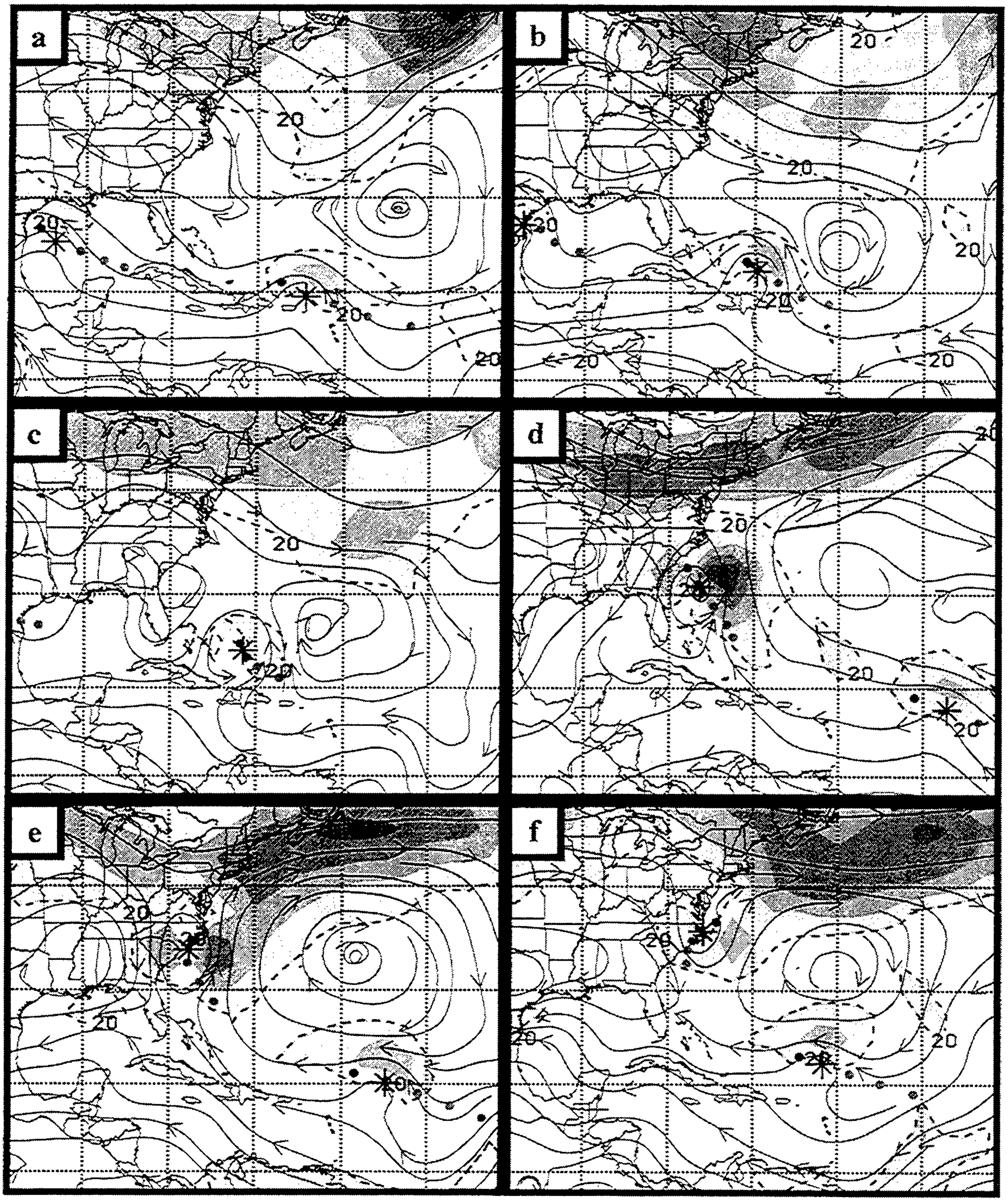

Fig. 21 NOGAPS 500-mb analyses as in Fig. 4, except at 1200 UTC on (a) 21 August, (b) 22 August, (c) 23 August 1998, and 0000 UTC on (d) 26 August, (e) 27 August, and (f) 28 August.

Bonnie is equatorward of the subtropical anticyclone axis, it is still in the S/PF pattern/region. The synoptic situation is still characterized as a S/PF pattern/region 12 h later (see Fig. 4b), except the translation speed of Bonnie has begun to decelerate (9 kt) as it approaches the subtropical anticyclone axis, and the steering flow over Bonnie is being influenced by oppositely-directed circulations to the east and to the west.

At 0000 UTC 27 August (Fig. 21e), Bonnie is near the subtropical axis and has slowed to a 6-kt translation speed. Thus, the environment structure of Bonnie is in a transitional state between the S/PF and the Midlatitude (M)/PF pattern/region (Fig. 18). Notice that the subtropical anticyclone cells to the east and to the west have both amplified over the past 24 h (compare with Fig. 21d) as a midlatitude ridge-trough-ridge circulation has come into phase, which is an example of the MCG transitional mechanism in Fig. 14a-b. The eastern subtropical anticyclone cell continues to be the dominant circulation, as indicated by the 40-kt isotach to the east versus the 30-kt isotach to the west of Bonnie. Notice also that the eastern isotach maximum is better connected with the midlatitude isotach maximum than on the western side, which suggests a stronger steering influence on Bonnie may come from the eastern anticyclone. Clearly, this is a difficult forecast situation given the opposing steering influences of the eastern and western anticyclones, along with the potential TC structure changes as part of the circulation is over land and part remains over the Gulf Stream.

After 24 h (Fig. 21f), the dominance of the eastern anticyclone circulation on the steering flow of Bonnie is much more evident. Bonnie is still moving slowly (7 kt), but is on a heading toward 56°. In addition, the isotach maximum has shifted to the east-southeast of Bonnie. Thus, the transition to the M/PF pattern/region has been completed. Although the midlatitude flow to the north is strong enough and fairly zonal, Bonnie is still on the northwestern flank of the eastern subtropical anticyclone, and the region classification of PF is more appropriate than the M/Midlatitude Westerlies (MW) pattern/region combination (see Fig. 18). As Bonnie moves into the tightened pressure gradient between the midlatitude circulation and the subtropical anticyclone to the south, its translation speed will increase (maximum 32 kt) and it will turn more eastward in the M/MW pattern/region (not shown).

[Note: TC Danielle has entered the domain in Fig. 21d well equatorward of the eastern subtropical anticyclone. The isotach maximum is on the poleward side as expected with a S/TE pattern/region. By 0000 UTC 27 August (Fig. 21e), Danielle is still in the S/TE pattern equatorward of the strengthened eastern anticyclone. Consequently, Danielle continues to move to the west (heading 286°) at 12 kt on 0000 UTC 28 August (Fig. 21f). Without any disrupting influences from adjacent synoptic circulations, the environment structure remains the same and no significant track changes occur during this period.]

2. <u>TC Sebastien (S/PF $\rightarrow$ S/EF)</u>. In the recurvature-type track as in TC Bonnie, the poleward motion in the Standard (S)/Poleward Flow (PF) pattern/region causes the TC to cross the subtropical anticyclone axis into the Midlatitude (M)/PF pattern/region and the TC then has an eastward motion. Depending on the amplitude and positioning of the midlatitude trough, the TC may then accelerate eastward in the M/Midlatitude Westerlies (MW) pattern/region. However, not all TCs in the S/PF pattern/region complete recurvature. Some TCs, such as Sebastien during 1995, turn southwestward (Fig. 22), which is an extreme version of a "stairstep"

track. At 0000 UTC 22 October, Sebastien was moving almost northward (heading 353°) at 9 kt, and just 24 h later was moving toward 231° at 11 kt. A forecast of a classical recurvature track for Sebastien would have resulted in very large track errors.

TC Sebastien was a late-season TC. Although the track of Sebastien was not directly affected by the passage of a high amplitude, progressive midlatitude trough-ridge system, it was indirectly affected by the midlatitude circulation. At 1200 UTC 21 October (Fig. 23a) Sebastien was in the S/PF pattern/region on the west-southwestern flank of a subtropical anticyclone that extended southeast-to-northwest to join a midlatitude ridge. A vigorous midlatitude trough over the eastern U.S. has suppressed the western subtropical anticyclone over Cuba. Another midlatitude trough to the northeast of Sebastien is contributing to the tilt of the eastern subtropical anticyclone. A midlatitude anticyclone is between these troughs, but is currently too far to the north to currently affect Sebastien.

During the next 24 h (Fig. 23b), amplification of this eastern midlatitude trough weakens the eastern subtropical anticyclone, and thus decreases the poleward steering flow over Sebastien. In addition, the midlatitude trough over the U. S. has "lifted out" and a marked restoration or amplification of the western subtropical anticyclone has occurred. Finally, and perhaps most importantly, the midlatitude anticyclone has moved southward to 40°N, 56°W and has connected to the strengthening subtropical anticyclone to the northwest of Sebastien. At this time, Sebastien is heading toward 259° at 8 kt (Fig. 22), which indicates that the steering influence of the large western subtropical/midlatitude anticyclone has become more dominant than the eastern subtropical anticyclone. Thus, the environment structure has undergone a transition from the S/PF to the S/Equatorward Flow (EF) pattern/region (Fig. 18) via the Midlatitude AnticycloGenesis (MAG) transitional mechanism.

By 1200 UTC 23 October (Fig. 23c), Sebastien is clearly in the S/EF pattern/region as the western subtropical anticyclone is now the dominant circulation. The southward shift of the eastern midlatitude trough has further depressed the amplitude of the eastern subtropical anticyclone, which is now only a ridge along 15°N. The eastern Atlantic circulation now resembles the Upper-level (U) low synoptic pattern (Fig. 18), except Sebastien is too far southwest to be affected by this circulation. The isotach maximum has shifted to the northwest of Sebastien, which is consistent with the motion toward 228° at 8 kt. Whereas even 36 h previously Sebastien had been moving poleward away from the Windward Islands, it has now changed course and is headed toward the islands. Fortunately, vertical wind shear has reduced the intensity from 55 kt at 1800 UTC 22 October to only 40 kt. Even at 0815 UTC 22 October (Fig. 24a) before achieving maximum intensity, it was evident that Sebastien was being exposed to considerable vertical wind shear. Notice the lack of deep convection to the west, the sharp western edge of the deep convection, and the cirrus streaming eastward. This synoptic pattern/region continues during the next 24 h (Fig. 23d), and Sebastien does strike the Windward Islands. However, the intensity was only 30 kt. The effect of vertical wind shear is again evident in the satellite image at 1115 UTC 24 October (Fig. 24b).

As indicated in the transition summary diagram (Fig. 19), the S/PF → S/EF transition occurred 10 times during this nine-year sample. Although this transition is not very frequent, the potential for a large track forecast error exists if a classical recurvature is predicted and the TC

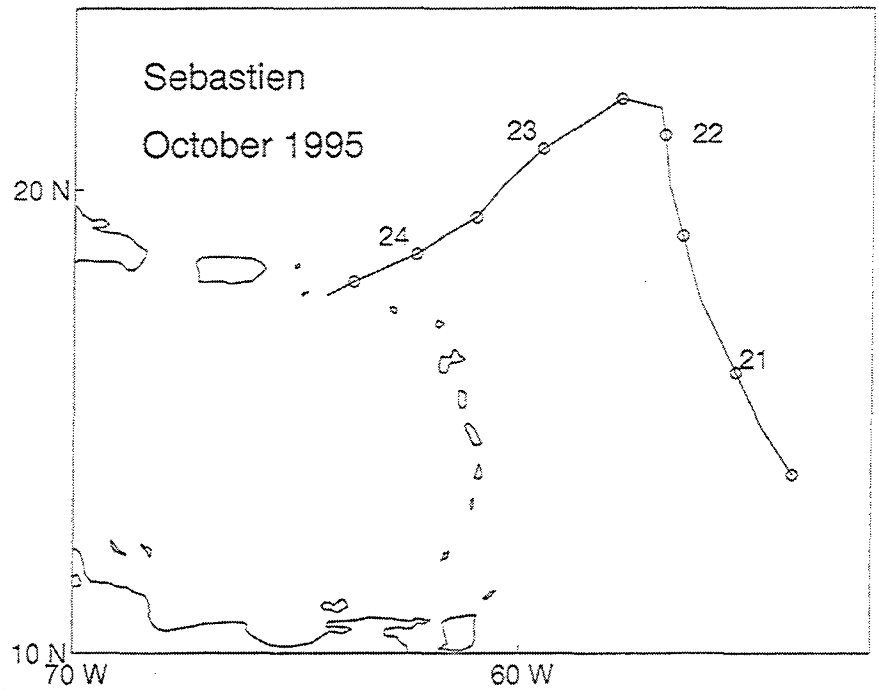

Fig. 22. Track as in Fig. 20, except for TC Sebastien.

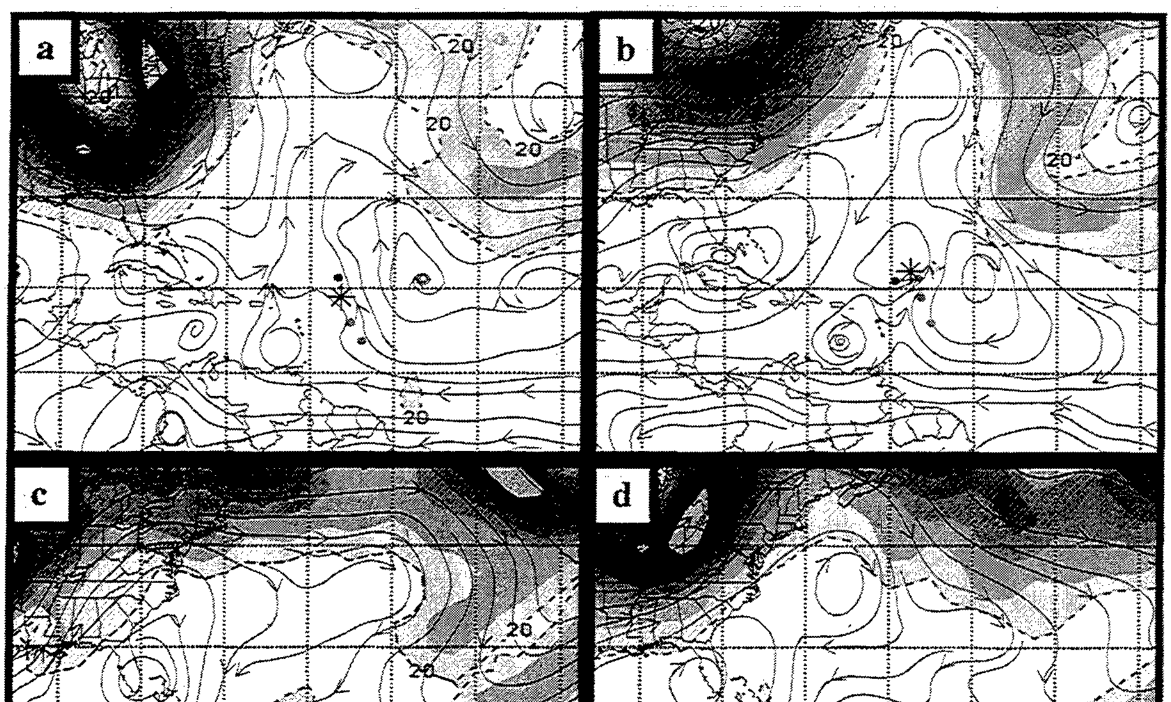

Fig. 23. NOGAPS 500-mb analyses as in Fig. 4, except at 1200 UTC on (a) 21 October, (b) 22 October, (c) 23 October, and (d) 24 October 1995.

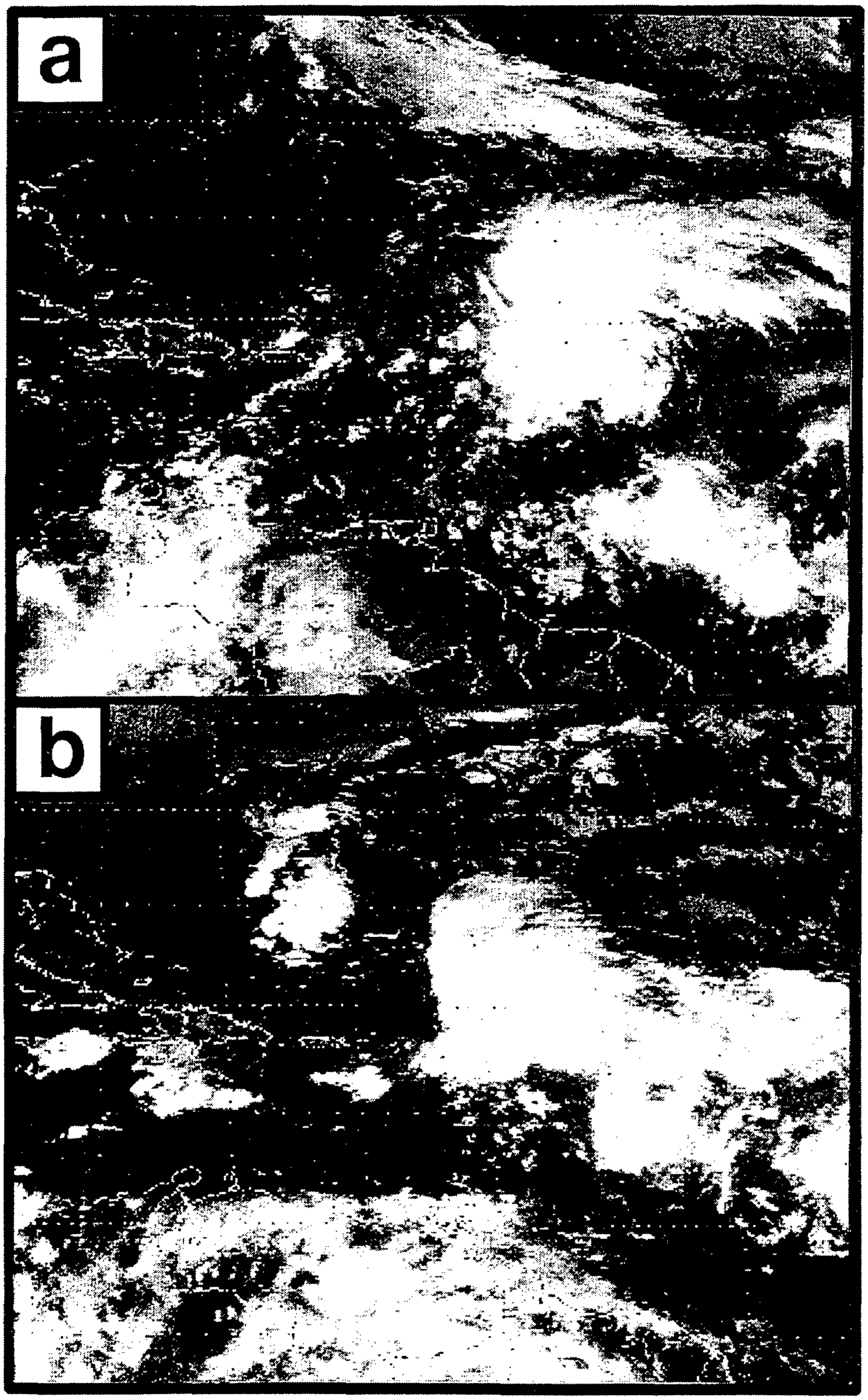

Fig. 24. Satellite infrared imagery of TS Sebastien at (a) 0815 UTC 22 October and (b) 1115 UTC 24 October 1995.

turns southwestward. As illustrated in this example, the dominant circulation shifts from the eastern subtropical anticyclone to the western subtropical anticyclone. An accurate and timely forecast of this abrupt track change requires guidance that correctly predicts the changes in both subtropical anticyclone cells. In this late-season case, these relatively weak subtropical anticyclone circulations were being strongly modulated by a large amplitude midlatitude trough-ridge-trough system. Consequently, one may consider that the TC track changes are being affected by midlatitude circulations quite remote from the TC.

3. <u>TC Luis (S/TE → P/EF → S/TE → P/PF)</u>. In the Bonnie example (Fig. 20-21) of a recurvature, the track changed from westward motion in the Standard/Tropical Easterlies (S/TE) pattern/region to northwestward motion in the S/Poleward Flow (PF) on the southwestern flank of a subtropical anticyclone cell (Fig. 18). That is, the TC approaches the recurvature point at the subtropical anticyclone axis simply as a result of advection by a steering flow established by a subtropical anticyclone circulation to the northeast. Presentation of this case study of TC Luis has two purposes. The first purpose is to illustrate an equatorward track deflection following a transition from the S/TE to the Poleward (P)/Equatorward Flow (EF) pattern/region via the Indirect Cyclone Interaction (ICI) transitional mechanism (Fig. 5). The second purpose is to describe a poleward turn of Luis toward the subtropical anticyclone axis that is established during a S/TE to P/PF transition. Hurricane Luis at 0000 UTC 8 September 1995 is presented in Fig. 7b as an example of a P/PF environment structure. Characteristic P/EF and P/PF tracks are illustrated in Figs. 9 a-b. Notice that poleward motion may originate at low latitudes in the P/PF synoptic pattern/region.

As indicated in the transition summary diagram (Fig. 19), the S/TE → P/EF and the P/EF → S/TE transitions are relatively rare with only five and eight cases, respectively, in the nine-year sample. However, the S/TE → P/PF transition occurred 21 times during 1990-98. Given the significant track change from westward in the S/TE pattern/region (Fig. 6a) to poleward in the P/PF pattern/region (Fig. 9b), the forecaster needs to be alert to this transition.

The track of Hurricane Luis during this period is provided in Fig. 25. Early in the period, Luis was moving west-northwestward in the S/TE pattern/region. From 0600 UTC 3 September to 0600 UTC 4 September, Luis then moved south of west in the P/EF pattern/region. Beginning at 0600 UTC 4 September, Luis begins to move westward and is then classified in the S/TE pattern/region. On 7 September, Luis was moving northwestward toward the subtropical anticyclone axis in the P/PF pattern/region.

The synoptic map sequence at 500 mb during the S/TE → P/EF → S/TE → P/PF transitions is provided in Fig. 26. At 1200 UTC 2 September 1995 (Fig. 26a), Luis is near 17°N, 48°W and is equatorward of a large circular subtropical anticyclone centered near 32°N, 47°W. As expected for a TC in the S/TE pattern (Fig. 18), the isotach maximum is northeast of Luis. To the northwest of Luis, TC Iris (near 27°N, 60°W) and TC Karen (near 31°N, 59°W) are undergoing a Direct Cyclone Interaction (DCI) transitional mechanism (Fig.10) with an eventual merger. The combined Rossby wave dispersion from these two TCs is creating a peripheral anticyclone in their wake, which is evident in Fig. 26a as an anticyclonic circulation extending southwestward from the subtropical anticyclone.

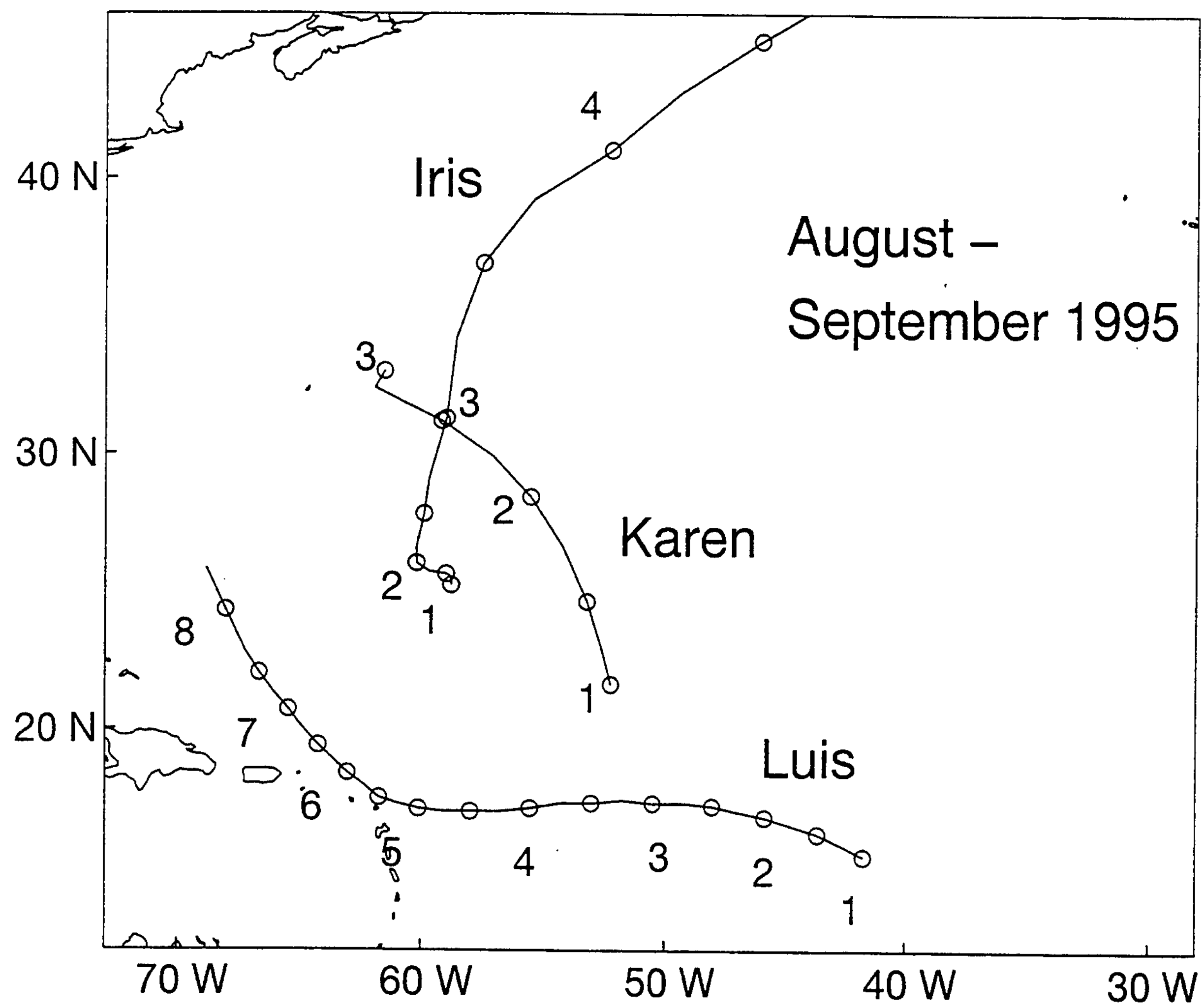

Fig. 25. Tracks as in Fig. 20, except for (southern) Hurricane Luis and (northern) TCs Karen and Iris that merge during this period.

The development of a peripheral anticyclone to the southeast (Northern Hemisphere) of a TC was evident in the non-divergent, barotropic simulations of TC motion on a beta plane (see description in Elsberry 1995). As indicated in Fig. 27, the Rossby wave dispersion leading to the peripheral anticyclone trailing the TC is much greater for a large TC (panel b) than for a small TC (panel a). The distortion of the initially circular TC on a beta plane leads to an asymmetric structure with cyclonic (anticyclonic) vorticity advection to the northwest (southeast). As illustrated in Fig. 27b, the cyclonic vorticity advection causes a col (break) in the subtropical anticyclone axis as the TC propagates to the northwest. The peripheral anticyclone arises from the anticyclonic vorticity advection to the southeast. Farther to the southeast, a region of cyclonic vorticity tendency favors development of another cyclone in this Rossby wave train. With the development of a subtropical anticyclone break and the extension of the peripheral anticyclone to join the eastern subtropical anticyclone, the environment structure is changed from the S/TE (Fig. 27c) to the P/PF (Fig. 27d) pattern/region. This is the Ridge Modification by a TC (RMT) transitional mechanism (Fig. 2). The TC track change that follows a S/TE → P/PF transition is from westward to poleward, so that the combined Iris-Karen circulation is expected

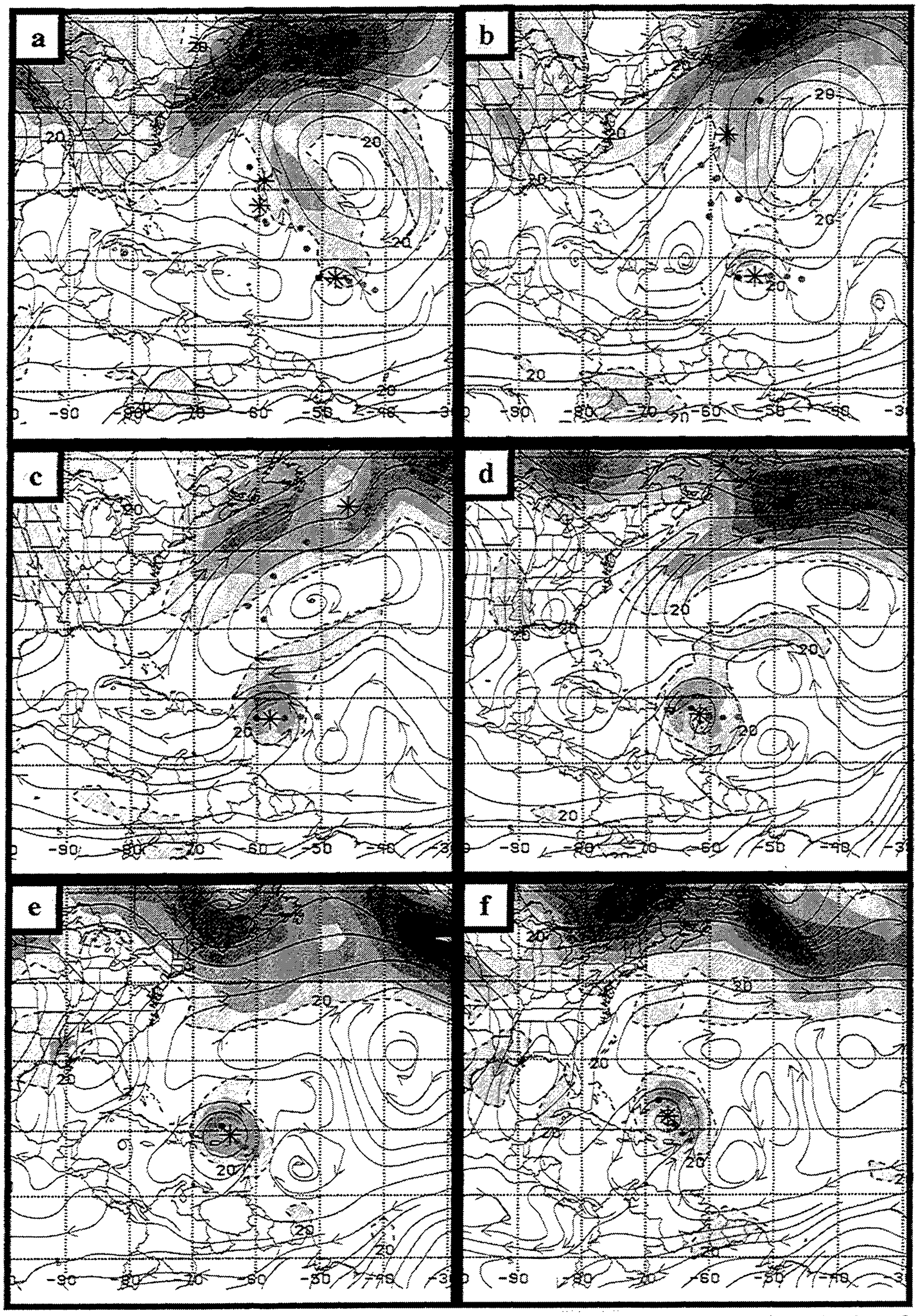

Fig. 26. NOGAPS 500-mb analyses as in Fig. 4, except at 1200 UTC on (a) 2, (b) 3, (c) 4, (d) 5, (e) 6, and (f) 7 September 1995.

to move poleward. However, Hurricane Luis is trailing the Iris-Karen peripheral anticyclone (Fig. 26a) and is expected to have an equatorward steering flow in the P/EF pattern/region.

The peripheral anticyclone trailing the merged circulation of Karen and Iris is more evident at 1200 UTC 3 September (Fig. 26b). This strengthening is due in part to the approach of the midlatitude trough, which, like Karen-Iris, also disperses negative vorticity to its southeast. With Karen-Iris and this trough building the peripheral anticyclone to the northwest of Luis, an equatorward steering component is established over Luis, which is indicated by the shift of the isotach maximum to the northwest. Even though the merged circulation of TC Iris and TC Karen has just exited the region (four dots from 32°N, 69°W to 41°N, 62°W indicate the -48 h through -12 h positions) at 1200 UTC 4 September (Fig. 26c), Hurricane Luis has become the eastern TC in the P/EF pattern/region of Fig. 18. This Indirect Cyclone Interaction of Iris-Karen and the trough, their peripheral anticyclone, and Luis as it affects the track of Luis is an example of ICIE (Fig. 5c) of the Meteorological knowledge base (Fig. 2, lower right).

Continued evidence that Luis had been in the P/EF pattern/region, and has now completed a transition to the S/TE pattern/region, is that the isotach maximum in Fig. 26c is just to the north-northwest of Luis. In addition, the high winds extend southward more strongly on the west side than on the east side of Luis. The eastern isotach maximum is between Luis and its peripheral anticyclone, which is centered near 13°N, 48°W and is still relatively weak at this time. Nevertheless, the beginning of the peripheral anticyclone of Luis is another indication of the Ridge Modification by a TC (RMT) transitional mechanism as in Fig. 27, which has the potential to change the dominant steering influence of Luis. That is, this second peripheral anticyclone may eventually extend from the southeast to northeast of Luis and thus exert a poleward steering over Luis if this RMT process continues. Thus, the forecaster must monitor the development of this peripheral anticyclone.

During the next 24 h (Fig. 26d), the peripheral anticyclone to the southeast of Luis near 13°N, 50°W has increased in size. However, this anticyclone is not well-developed to the east and northeast of Luis as in the P conceptual model (Fig. 18) because of the downward penetration of an upper-level low at 23°N, 49°W. Supporting evidence for the existence of this upper-level low to the northeast of Luis is the satellite infrared images in Fig. 28a-b. In addition to the small, deep convection cells around the center of the upper-level low, some bandiness in the clouds is also evident. This upper-level low inhibits development of the peripheral anticyclone of Luis, which thus inhibits the poleward steering across Luis, and this is designated as an ICIW (Fig. 5) for Luis. Although the peripheral anticyclone of Luis is being inhibited to the northeast, it is beginning to exert a poleward steering component over Luis, which is now moving toward 297° at 8 kt (Fig. 25). This clockwise change in heading of 27° during the past 24 h occurs even though the southwest-northeast tilted anticyclone still exists to the northwest, which is exerting a southward steering component over Luis as indicated by the continued southward extension of the isotach maximum west of Luis.

By 1200 UTC 6 September (Fig. 26e), the peripheral anticyclone to the southeast of Luis near 14°N, 53°W has amplified. The southeastward extension of the isotach maximum toward this peripheral anticyclone implies a more poleward component compared to the shrinking of the isotach maximum to the west of Luis, which indicates a decrease in the equatorward steering

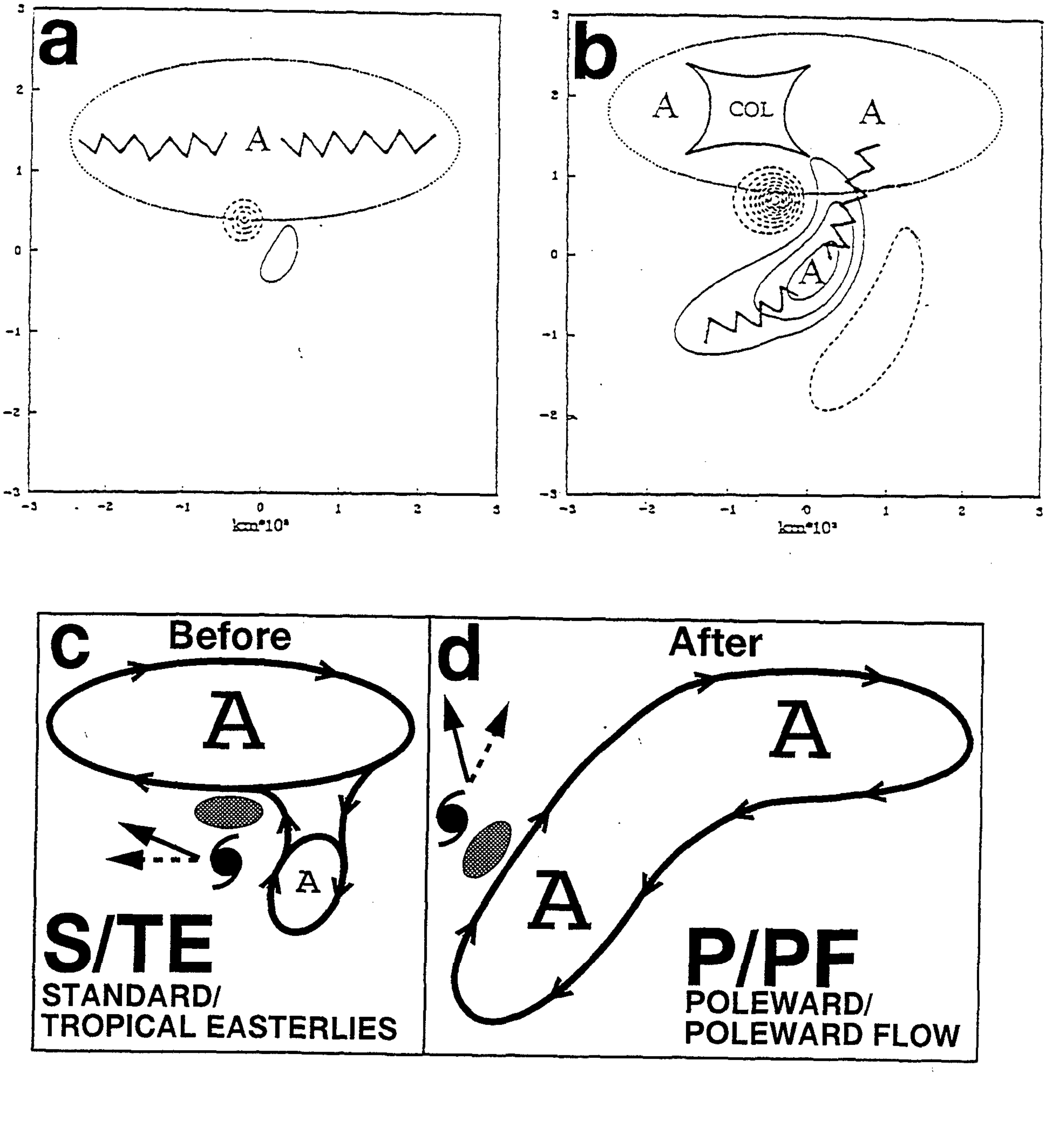

Fig. 27. Rossby wave dispersion from a (a) small or (b) large TC (dashed streamfunction) south of the subtropical anticyclone (A) as simulated in a non-divergent barotropic model on a beta plane. Notice the development of a significant peripheral anticyclone to the southeast of the larger TC in panel (b). Conceptual model of the Ridge Modification by a TC (RMT) transitional mechanism in which the development of the peripheral anticyclone changes the synoptic pattern/region from (c) S/TE to (d) P/PF. The isotach maximum (shaded elliptical region) shifts from north of the TC in panel c to southeast in panel d, which indicates the change in the steering flow over the TC. Likely track orientations relative to the steering flow are indicated by a solid (dashed) arrow for a bigger (smaller) TC.

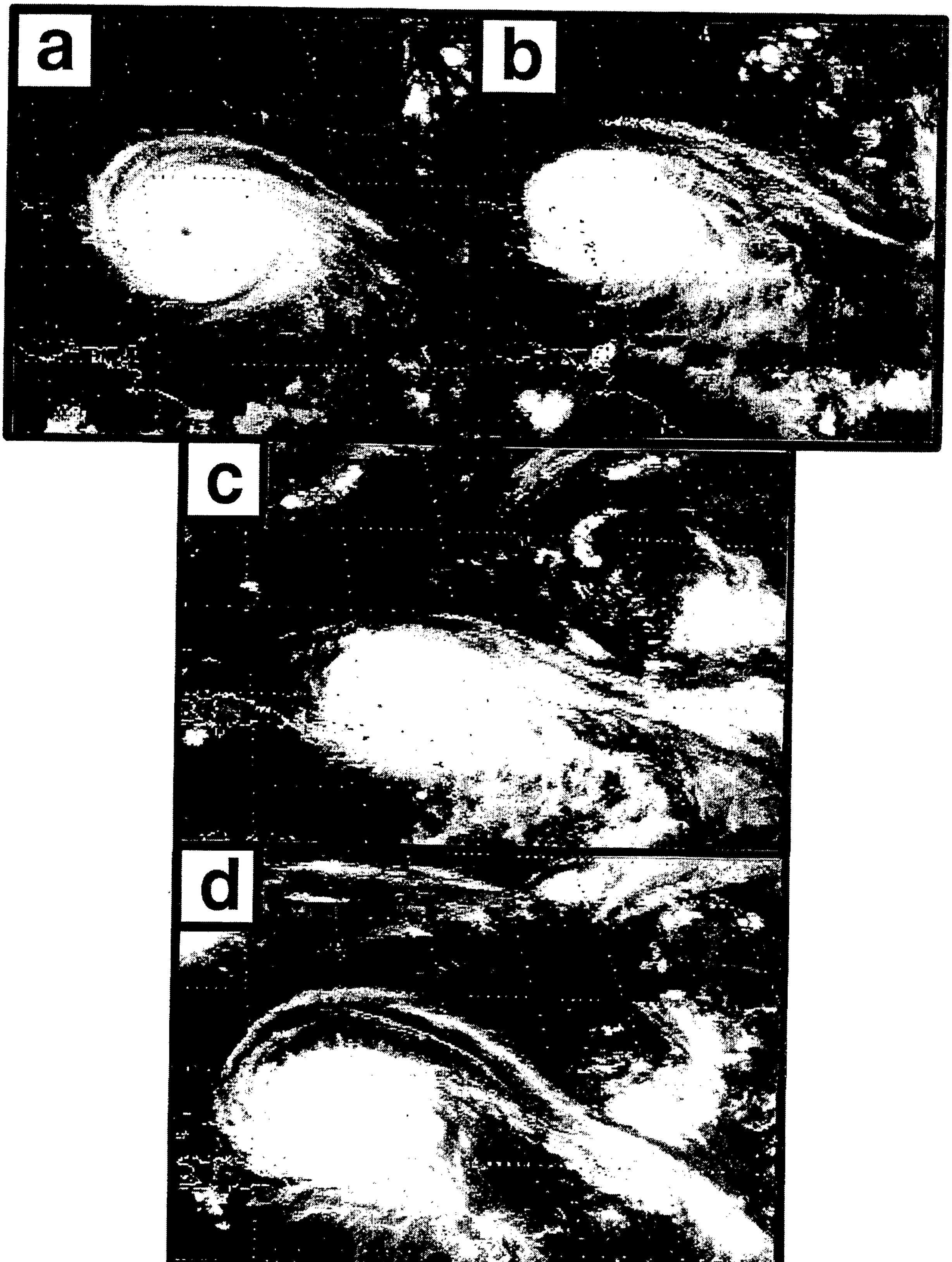

Fig. 28. Satellite infrared imagery as in Fig. 24, except for Hurricane Luis and an upper-tropospheric low to its northeast near 23°N, 49°W at (a) 1315 UTC 4 September, (b) 1315 UTC 5 September, (c) 1115 UTC 6 September, and (d) 1315 UTC 7 September 1995.

associated with the anticyclone to the northwest. Were it not for the continued (but weakened) presence of the cyclone (trough) to the northeast of Luis near 25°N, 54°W (see also satellite image in Fig. 28c), the peripheral anticyclone of Luis would have been stronger on the eastern side, and a stronger poleward steering flow would have been occurring. That is, the ICIW mechanism is still present, but the RMT mechanism is also present and the peripheral anticyclone has continued to amplify to the southeast. Nevertheless, Luis is now moving toward 314° at 9 kt, which is a further 17° clockwise heading change during the past 24 h. Thus, the environment structure is considered to have been in a transitional state during the past 24 h. This is indicated in the environment structure data base as a dual S/P pattern and a dual TE/PF region, where the first letter in each case indicates the present classification and the second letter indicates the pattern or region that will exist if the transition is completed. In this case, this dual designation of a transition in progress was applied from 1200 UTC 5 September (Fig. 26d) to 1200 UTC 6 September (Fig. 26e) as the track heading of Luis changed from 297° to 314°.

By 1200 UTC 7 September (Fig. 26f), the transition from the S/TE to the P/PF pattern/region has been completed, and the track heading is now 323° at 9 kt. The peripheral anticyclone has continued to develop and now is connected with an east-west oriented subtropical anticyclone to the north of Luis. Although the upper-level low is still evident in the satellite image (Fig. 28d), it is evidently far enough to the northeast of Luis that it is not interfering so much with the peripheral anticyclone circulation as at previous times. Even though a break in the subtropical anticyclone is not present, and the orientation of the peripheral anticyclone is more north-south than in the P pattern conceptual model (Fig. 18), a strong poleward steering component over Luis is indicated by the isotach maximum that extends from northwest clockwise to southeast of Luis. The analysis in Fig. 7b shows these tendencies continue in the following 12 h, and Luis recurves through the subtropical anticyclone axis 24 h after that analysis.

4. TC <u>Danielle (S/TE → P/PF→ M/PF</u>). Another example is given here of the S/TE →P/PF transition (21 cases in Fig. 19), because of its importance in turning the TC poleward at low latitudes, and of the frequent transition P/PF → M/PF (17 cases in Fig. 19). That is, once a TC is in the P/PF pattern/region, the chances it will continue poleward in either the M/PF or the S/PF (4 cases) are much greater than it will experience a transition to the S/TE pattern/region (4 cases) and change to a westward track (i.e., a stairstep track). A second reason for this case study is that TC Earl also turns poleward over the Gulf of Mexico almost simultaneously with the S/TE → P/PF transition of Danielle in a transitional mechanism called Reverse-oriented Trough Formation (RTF) in Fig. 2 (bottom). While this RTF transitional mechanism is fairly common in the western North Pacific, it is rather rare in the Atlantic because it requires two TCs to be in near-proximity and to have an east-west orientation.

The tracks of Danielle and Earl are illustrated in Fig. 29. Although Danielle was following the track of Bonnie (Fig. 20) and encountered the pool of cold water created where Bonnie nearly stalled for 2 days, it took a more poleward path than did Bonnie when the environment structure changed to the P/PF pattern/region at 0000 UTC 31 August 1998. During the S/TE → P/PF transition, the track heading of Danielle changed from 304° at 10 kt on 0000 UTC 30 August to 342° at 6 kt on 0000 UTC 31 August. Consequently, Danielle no longer posed a threat to the east coast of the U.S. Rather, Danielle proceeded northward in the P/PF

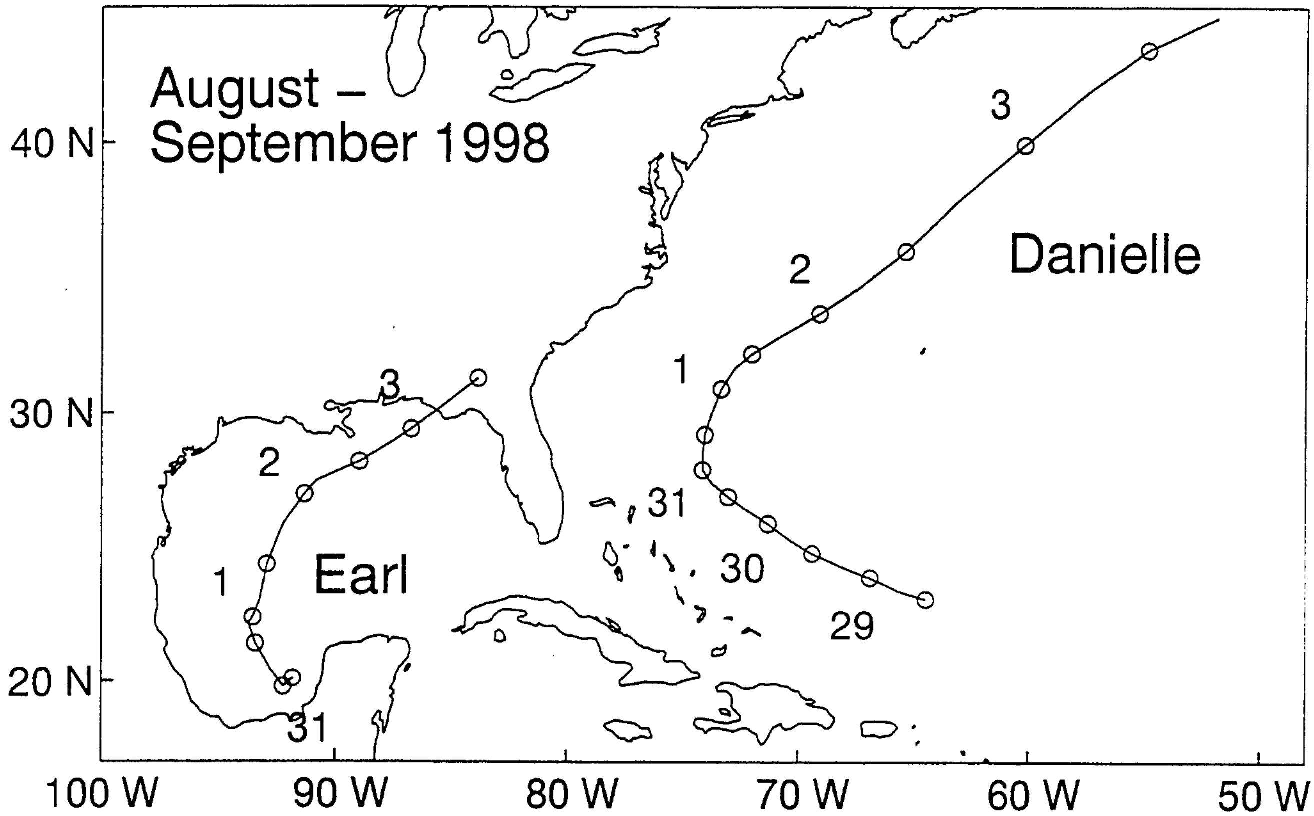

Fig. 29. Tracks as in Fig. 20, except for (eastern) TC Danielle and (western) TC Earl.

pattern/region and at 0000 UTC 2 September was in the M/PF pattern/region with a heading of 57° at 16 kt. Just 24 h later, the storm translation had increased to 30 kt with a heading of 30°. Meanwhile, TC Earl initially drifted westward off the Yucatan Peninsula and slowly intensified over the Gulf of Mexico. Almost immediately Earl turned poleward in the P/PF pattern/region by 1200 UTC 31 August. Just 12 h later, Earl had a heading of 27° at 5 kt. Earl then accelerated northeastward to a translation speed of 15 kt. Earl achieved hurricane intensity at 1800 UTC 2 September before striking the Florida panhandle coast.

The synoptic map sequence in Fig. 30 begins 24 h after Fig. 21f. At 0000 UTC 29 August (Fig. 30a), TC Bonnie is near 38°N, 71°W and is moving toward 56° at 17 kt while in a transitional state between the M/PF and the M/MW pattern/region. Danielle is near 24°N, 67°W and is moving westward (heading 292°) at 12 kt. Danielle is equatorward of a well-established subtropical anticyclone with an isotach maximum to the north, and thus is in the S/TE pattern/region.

By 0000 UTC 30 August (Fig. 30b) the translation speed of Bonnie has increased to 32 kt toward 64° so that it has almost completed the transition to the M/Midlatitude Westerlies (MW) pattern/ region (Fig. 18). Bonnie then dissipated 18 h later. Meanwhile, Danielle has begun to turn poleward (304° at 10 kt) and is in a transitional state between the S/TE and the P/PF pattern/region. Notice that the isotach maximum has begun to shift from almost north of

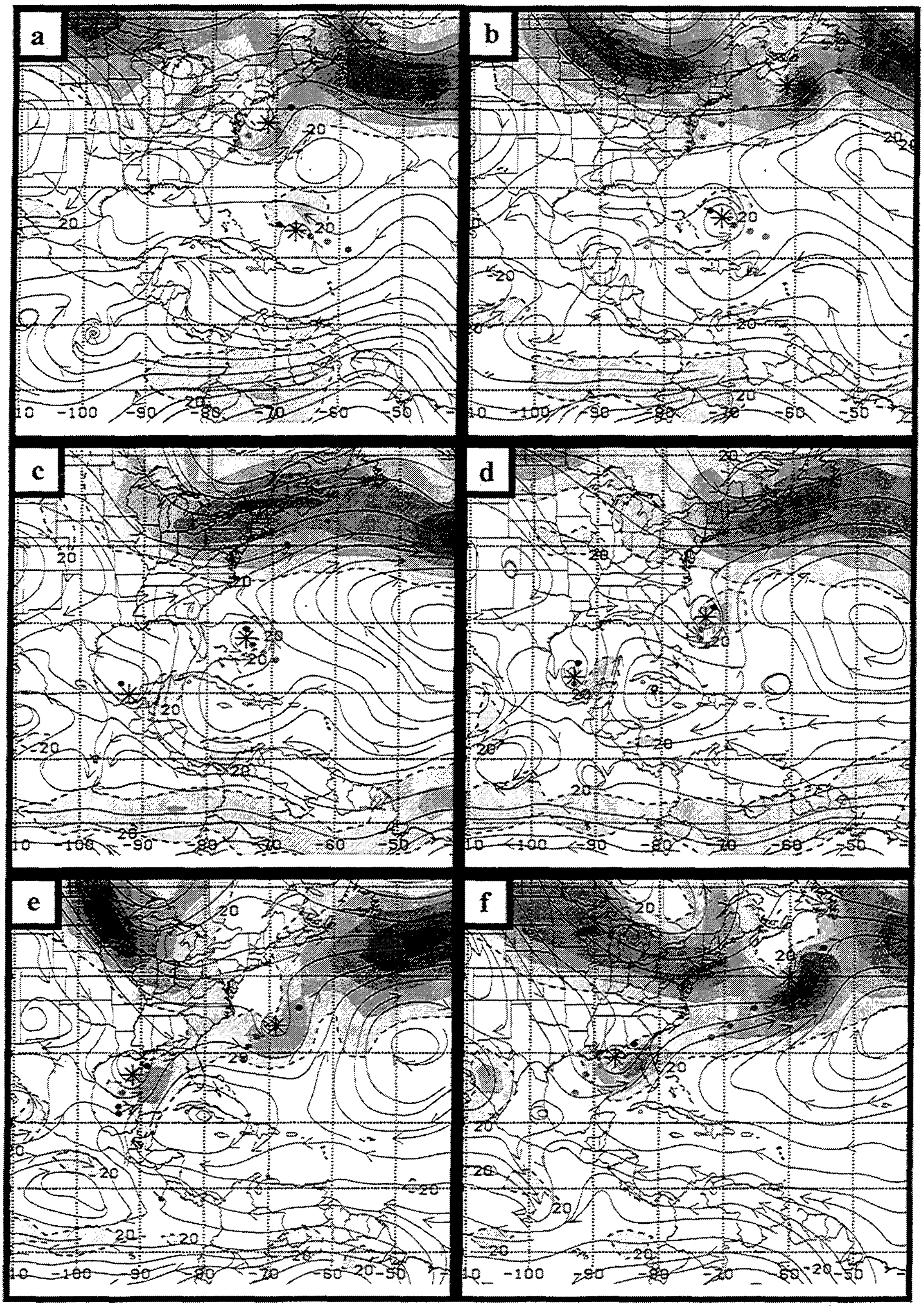

Fig. 30. NOGAPS 500-mb analyses as in Fig. 4, except at 0000 UTC on (a) 29 August, (b) 30 August, (c) 31 August, and (d) 1 September, (e) 2 September, and (f) 3 September 1998 for eastern TC Danielle and western TC Earl.

Danielle to more northeast. The key development in the past 24 h has been the development of the peripheral anticyclone to the southeast of Danielle (compare Fig. 30b with Fig. 30a) as part of the Rossby wave dispersion from Danielle, which is the RMT transitional mechanism (Fig. 27). It is the steering flow associated with the peripheral anticyclone that is introducing a poleward motion component to Danielle, since the subtropical ridge to the north extends westward to at least 90°W, which would imply a continued westward motion.

By 0000 UTC 31 August (Fig. 30c), it is more evident that Danielle is moving toward the subtropical anticyclone axis rather than moving westward parallel to the axis. The isotach maximum to the northeast, and that Danielle is on the southwestern flank of the subtropical anticyclone to the east, would suggest a transition to the S/PF pattern/region (Fig. 18). However, a 20-kt isotach maximum also is present to the south-southeast of Danielle (Fig. 30c) in conjunction with the peripheral anticyclone to the southeast, which confirms that the S/TE → P/PF transition is now complete.

Notice in Fig. 30c that TD Earl has formed near 20°N, 92°W from a cyclonic circulation that had been over the Yucatan Peninsula 24 h earlier (Fig. 30b). Although Earl is drifting toward 293°, a peripheral anticyclone is already developing and the isotach maximum is clearly to the east of Earl, rather than to the north of Earl as might be expected for a S/TE pattern/region. As illustrated in the RTF conceptual model (Fig. 31), the Rossby wave dispersion from two TCs oriented west-southwest to east-northeast may lead to a merging of the two peripheral anticyclones and create a long ridge to the southeast of the two TCs, resulting in the P pattern schematic illustrated in Fig. 18. In conjunction with a combined trough to the northwest that is also oriented WSE-ENE, a poleward and eastward steering component is introduced over the TCs. Lander (1994) has termed this a reverse-oriented monsoon trough as it is tilted north of east rather than south of east as in the climatological summer monsoon trough in the western North Pacific. Notice that the extended peripheral anticyclone from southeast of Danielle to east of Earl has many of the characteristics of this RTF conceptual model of Carr and Elsberry (1994). In this case, Earl is moving poleward in the poleward flow on the west end of the long peripheral anticyclone rather than moving eastward in P/EW on its north side. The basic Rossby wave dispersion dynamics of the RTF transitional mechanism are the same as in the RMT transitional mechanism, except that two nearby TCs in a basically east-west orientation have to co-exist so their peripheral anticyclones merge. When this occurs, both TCs achieve a poleward steering component and they tend to turn poleward almost simultaneously, and this occurred with Danielle and Earl (Fig. 29).

By 0000 UTC 1 September (Fig. 30d), the peripheral anticyclone to the east-southeast of Earl is quite marked. Since the associated isotach maximum is also to the east-southeast of Earl, the transition from the S/TE to the P/PF pattern/region is complete for Earl. One of the special characteristics of the P pattern (Fig. 18) is that the TC track is turned poleward at low latitudes (Fig. 9a), and this is the case for Earl, which has an east-of-north heading (27°) even though it is well equatorward of the subtropical anticyclone axis. Since Danielle is just south of a westward extension of the Atlantic subtropical anticyclone, it is in a transitional state to the M/PF pattern. Although the isotach maximum is to the east of Danielle, the isotach maximum wraps around to the south, which is consistent with a continued presence of the peripheral anticyclone.

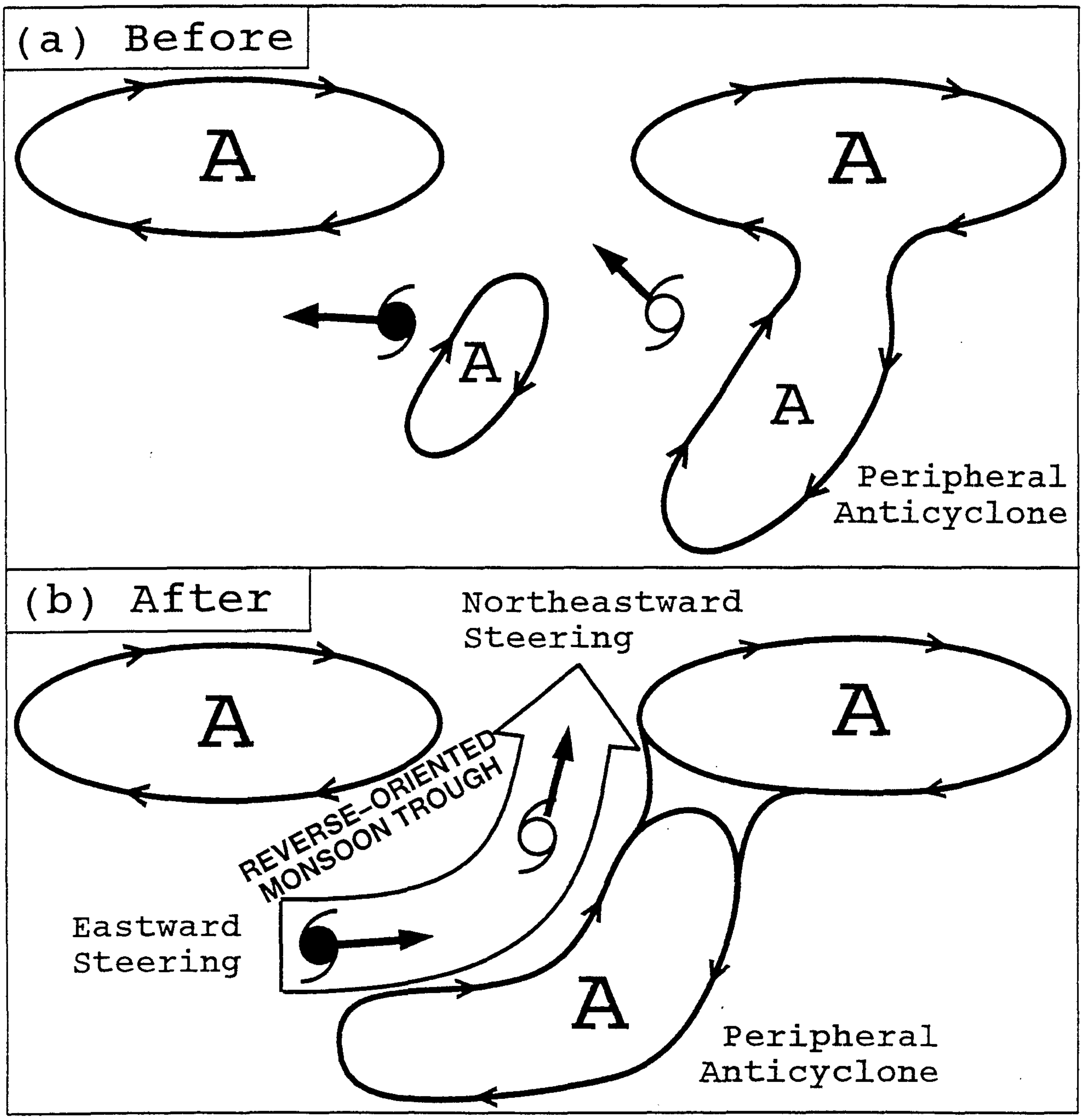

Fig. 31. Conceptual model as in the RMT conceptual model in Fig. 27, except for the Reverse-oriented Trough Formation (RTF) that involves two TCs that initially were in an east-west orientation.

By 0000 UTC 2 September (Fig. 30e), Danielle has moved poleward of the subtropical anticyclone axis. The isotach maximum to the southeast of Danielle is well-developed, which reflects the amplification of the anticyclone. The translation speed of Danielle has increased to 16 kt with a heading of 57°. Thus, the environment structure of Danielle is in the M/PF pattern/region. A pronounced peripheral anticyclone to the southeast of Earl is clearly the dominant contributor to the steering flow over Earl, which is moving toward 38° at about 10 kt. Since Earl is still equatorward of the subtropical anticyclone axis, it is in the P/PF pattern/region.

Similar conditions exist 24 h later (Fig. 30f). The translation speed of Danielle has increased to 30 kt with a heading of 47° (Fig. 29). The Atlantic subtropical anticyclone, which still extends northward of Danielle east of 50° W, continues to be the dominant effect on the steering flow of Danielle as the midlatitude trough is still 15° long to the west. Thus, Danielle is still in the M/PF pattern/region. Earl is crossing the Gulf Coast. Although the peripheral anticyclone is not as marked as 24 h previously (compare Figs. 30f and 30e), Earl continues to be classified in the P/PF pattern/region. Given this analysis without knowledge of its previous history, the environment structure might have been listed as M/PF. That is, the blending of the peripheral anticyclone with the Atlantic subtropical anticyclone has made it seem that the anticyclonic axis is suddenly equatorward of Earl. Similarly, it appears that Earl is now embedded in a midlatitude trough that extends southward. Consequently, the analysis could also have been interpreted as a M/PF rather than a P/PF pattern/region. Of course, the steering flow is toward the northeast in both regions, and the ambiguity between P/PF and M/PF is of little consequence to the track forecast for Earl.

In both the Danielle and Earl cases, the key circulation feature is the peripheral anticyclone to the southeast. An accurate prediction of the timing and amplification of this anticyclone from the Rossby wave dispersion is critical to forecasting the poleward turns of both TCs. As demonstrated by Carr and Elsberry (1997), the strength of the vortex outer structure is an important factor in the Rossby wave dispersion from a TC. Thus, accurate track guidance from a dynamical model in these situations requires a good initial condition specification and prediction of the outer wind structure. Even though it is the relative strength of the peripheral anticyclone contribution to the steering flow versus that of the subtropical anticyclone, the latter circulation must also be analyzed and predicted well. Whereas the eastern subtropical anticyclone continued to play an important role in the track of Danielle, the peripheral anticyclone was clearly the dominant factor in the track of Earl. These distinctions must be handled well in the dynamical model guidance in these situations for the forecaster to make accurate forecasts and issue timely warnings.

5. <u>TC Karl (M/EF → M/PF) and TC Ivan (M/PF → M/MW)</u>. The tracks of (western) TC Karl and (eastern) TC Ivan are given in Fig. 32. During the 36-h period following 0000 UTC 25 September 1998, TC Karl changes from a heading toward 125° at 10 kt in the M/EF pattern/region to a heading toward 47° at 13 kt in the M/PF pattern/region. Even though Karl is poleward of 30°N the entire period, it actually intensifies from 50 kt to 75 kt over the 36-h period. During the same period, TC Ivan changes from a heading of 2° at 9 kt in the M/PF pattern/region to a heading of 73° at 26 kt in the M/MW pattern/region. Even with this translation speed increase and a poleward displacement from 34°N to 40°N, the intensity remains at 70 kt for the entire 36-h period.

Both TC Karl and TC Ivan are initially poleward of the subtropical anticyclone axis, which is zonally oriented at 25°N, and are well equatorward of the midlatitude westerlies north of 40°N (Fig. 33a). Both Karl and Ivan are in a trough region that tends to "break" the subtropical anticyclone axis. Karl and Ivan are involved in a Semi-direct Cyclone Interaction (SCI) as in Fig. 5a-b, which began twelve hours previous. The key effect of the SCIW (Fig. 5b) on the motion of the western TC Karl is that it is positioned between the high and the low pressures associated with the western subtropical anticyclone cell and Ivan, respectively, which

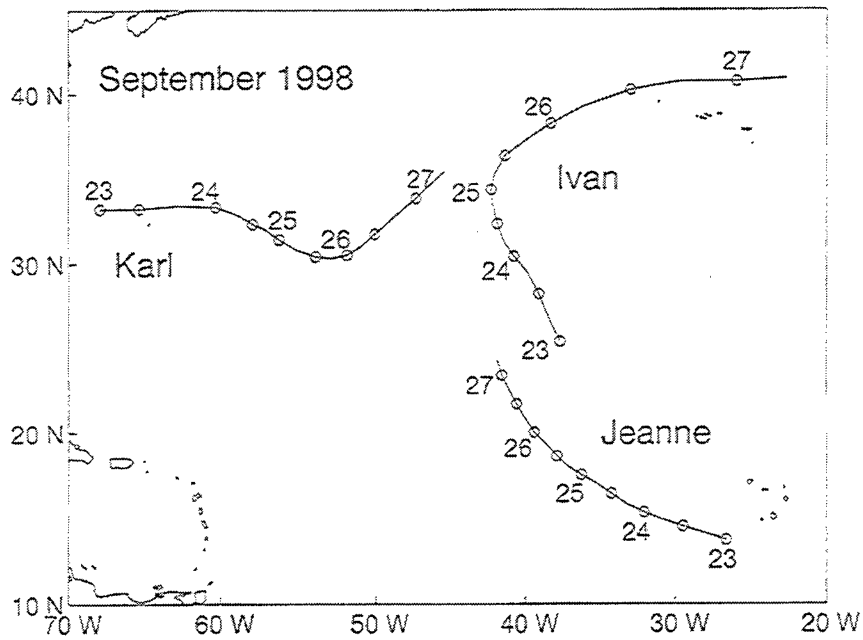

Fig. 32 Tracks as in Fig. 20, except for the (western) TC Karl and (eastern) TC Ivan.

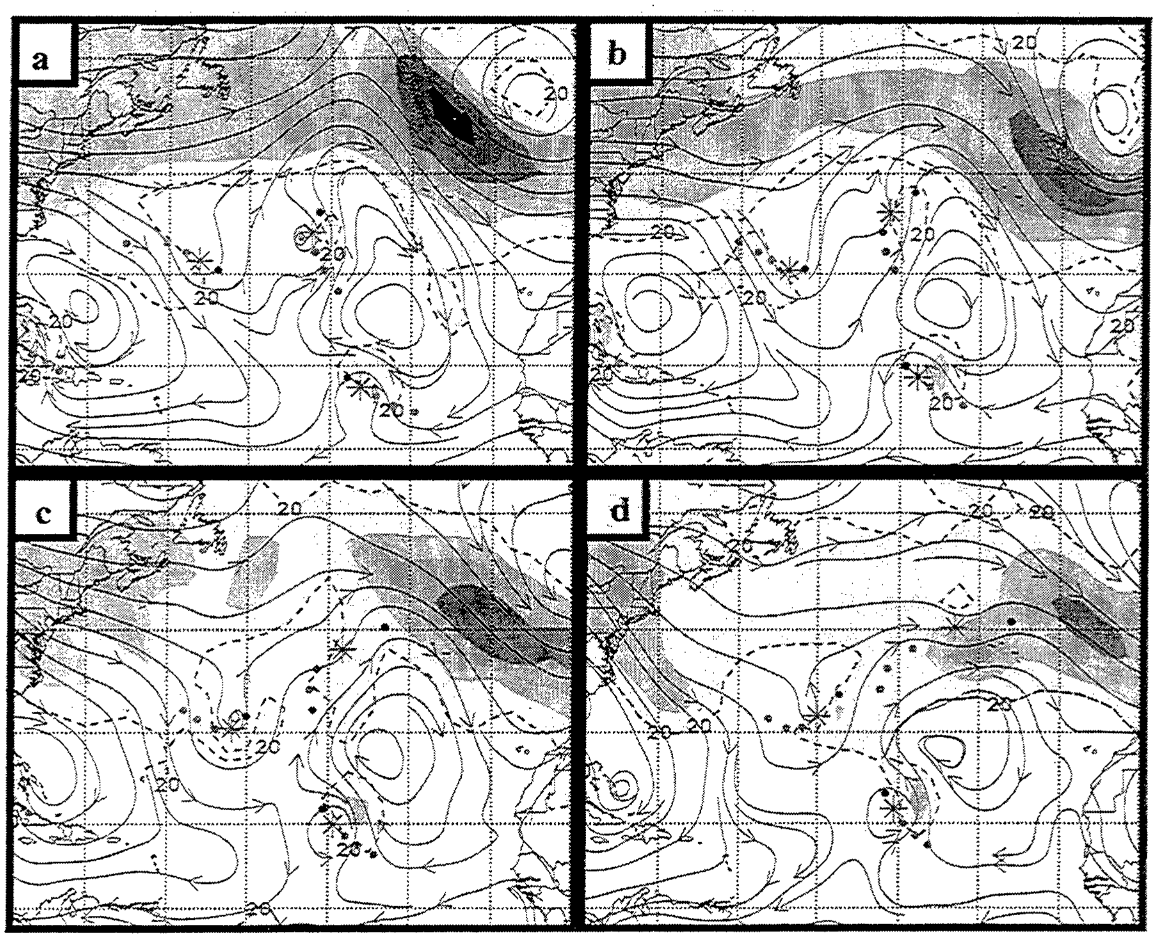

Fig. 33 NOGAPS 500-mb analyses as in Fig. 4, except at (a) 0000 UTC and (b) 1200 UTC 25 September, (c) 0000 UTC and (d) 1200 UTC 26 September 1998 for the western TC Karl and eastern TC Ivan. TC Jeanne is to the south of these two storms and Georges is on the western edge of panel a.

imposes an equatorward steering current over Karl. This advective component is in addition to a northwest-to-southeast steering flow on the northeastern flank of the subtropical anticyclone cell to the southwest. Since the isotach maximum is on the southwestern side of Karl, this TC is in the M/EF pattern/region of the conceptual model in Fig. 18. Similarly, the SCIE (Fig. 5a) effect on the eastern TC Ivan arises because it is positioned between the low and the high pressures associated with TC Karl and the eastern subtropical anticyclone cell, respectively, which imposes a poleward steering current over Ivan. This advective component is in addition to a poleward steering flow on the northwestern flank of the eastern subtropical anticyclone cell. Since the isotach maximum is on the eastern side of TC Ivan, this TC is in the M/PF pattern/region (Fig. 18). Given that Karl and Ivan are moving in opposite directions, the favorable SCI positions relative to the western and eastern subtropical anticyclone cells, respectively, do not persist.

By 1200 UTC 25 September (Fig. 33b), the midlatitude westerlies are becoming more zonal. TC Karl, which is now at the base of the weak trough, is moving toward 104° at 10 kt (Fig. 32). Since the isotach maximum is still to the west, Karl is still in the M/EF pattern/region. However, this is a transition situation toward the M/PF pattern/region. Ivan is still in the M/PF pattern/region since it continues to move poleward (toward 40° at 13 kt) with the isotach maximum to the east.

By 0000 UTC 26 September (Fig. 33c), TC Karl has passed around the base of the trough to the east side. Notice that the isotach maximum wraps around the base of the trough, with slightly stronger flow on the east side. Since Karl's heading is toward 66° at 9 kt, the transition from the M/EF to the M/PF pattern/region is still in progress. Meanwhile, TC Ivan has continued to translate along the northwestern flank of the eastern subtropical anticyclone. The isotach maximum to the east of Ivan is now connected with the 20-kt isotach associated with the midlatitude westerlies. Since the heading of Ivan is 56° at 18 kt, this is a transition state between the M/PF and the M/MW pattern/region.

The transitions to M/PF and to M/MW pattern/regions for TC Karl and TC Ivan, respectively, are completed by 1200 UTC 26 September (Fig. 33d). Notice that the isotach maximum is to the east of Karl, but is now to the south of Ivan (and is quite strong).

Both of these environment structure transitions are between synoptic regions within the M pattern. The forecast situation is difficult when the SCIW (SCIE) mechanism is contributing to the equatorward (poleward) translation of Karl (Ivan) early in the 36-h period. In addition to correctly analyzing and predicting the two subtropical anticyclone cells, the separation distance and the structures of the two TCs must be accurately predicted. Considering that all four circulations are moving and evolving, the opportunities for erroneous guidance are greater during the SCI period, which fortunately does not persist for more than about 24 h. Notice that the actual transitions are later accomplished by advection as indicated by the arrows in the conceptual model (Fig. 18). After the SCI period, the key to correct track forecasts during these transitions is an accurate analysis and forecast of the adjacent subtropical anticyclones that determine the steering currents over the two TCs. In the case of the eastern subtropical anticyclone, an interaction with the midlatitude westerlies must also be predicted to forecast the turn to the east and rapid acceleration of TC Ivan.

As indicated in Fig. 19, the M/PF → M/MW transition is the most common of all transitions since it occurred 30 times during the nine years. The M/EF → M/PF transition occurred less frequently, with only six transitions. It is certainly noteworthy that such changes in synoptic regions in the M pattern, and their associated track changes, occur at relatively high latitudes, and yet the TC may be at hurricane stage, as in the cases of Karl and Ivan. Clearly, these track changes are critical situations for maritime activities in the North Atlantic.

[Note: TC Jeanne also exists to the south of Karl and Ivan in Fig. 33. At the beginning of this 36-h period (Fig. 33a), Jeanne is in the S/TE pattern/region equatorward of the eastern subtropical anticyclone. As Jeanne is moving toward 314° at 9 kt at 1200 UTC 25 September (Fig. 33b), it is in a transition to the S/PF pattern/region. This transition is considered to be completed just 12 h later (Fig. 33c), even though the change of heading has just crossed 315°. At 1200 UTC 26 September (Fig. 33d), the heading is toward 328° and Jeanne is moving toward the break in the subtropical anticyclone axis. This S/TE → S/PF transition is thus accomplished by advection around the eastern subtropical anticyclone without external influences. Accurate track guidance for the relatively slow track change during this transition primarily depends on a correct analysis and prediction of the eastern subtropical anticyclone circulation. A secondary influence on the track prediction would be the beta-effect propagation, which requires an accurate initial TC structure specification and prediction.]

5. SUMMARY

The purpose of this report is to document a Meteorological knowledge base of dynamically-based conceptual models that classify various TC-environment situations in the Atlantic region (Fig. 2). The synoptic pattern/region models that have been applied to a sample of 1568 cases during 1990-98 are shown in Fig. 3. It is significant that one of these four patterns and six regions has been found to apply in every case. Using these pattern/region combinations, the Atlantic forecaster can develop a dynamically based "storyline" that explains the present and recent past motion based on knowledge of which circulations are determining the steering flow. Each pattern/region combination has characteristic tracks because of the commonality in the first-order steering flow (see Figs. 6, 8, 12, and 16).

A climatology of the frequency of synoptic patterns and regions (Fig. 17) has been prepared based on this nine-year sample. Almost half of the 1568 cases were in the Standard (S) pattern, with 30.5% of all cases in the S/Tropical Easterlies (TE) pattern/region that is characterized by long, west-northwestward tracks. About one-third (34.2%) of all of the Atlantic cases were in the Midlatitude (M) pattern north of the subtropical anticyclonic axis. A large variety of midlatitude circulation configurations, amplitudes, and tilts make the Atlantic TCs in the M pattern difficult to forecast. Even though most of these TCs in the M pattern have the expected tracks toward the pole or to the east, westward and equatorward motions are also possible. The special Upper-level (U) low synoptic pattern in the Atlantic also has an anomalous steering flow, including 1.8% of the 1568 cases with an initial equatorward steering component.

An essential first step in the track forecasting process is to establish an explanation for the recent past and present motion of the storm. Since environmental steering flow is normally the first-order contribution to tropical cyclone motion, the Meteorological knowledge base of the Systematic Approach is intended to help the forecaster establish the synoptic pattern and region. Since the conceptual models of the pattern/region combinations in Fig. 3 are rather idealized, a number of examples based on the NOGAPS analyses have been presented here to show some of the variety of environmental structures.

Table 1 is a summary of the operational analysis examples contained in this report, with figure numbers given for ease of review. In some cases, a reference is given to a figure in which the corresponding track is also given. In other cases, the figure number refers to the overall track summary for that pattern/region combination. Although it was not intended, the largest number of examples is for the S/TE pattern/region, as the examples of other pattern/regions often included a second (or third) TC that was in the S/TE pattern/region. Other frequently occurring examples in Table 1 are the S/PF, P/PF, and M/PF, which again reflects the greater frequency of occurrence for these pattern/region combinations (Fig. 17). Notice that some storms appear multiple times as the synoptic pattern/region changed along the path.

Another aspect of the Meteorological knowledge base (Fig. 2) is the transitional mechanisms that change the environment structure (synoptic pattern/region), and thus change the TC steering flow. Specific physical mechanisms have been identified that lead to these transitions (bottom of Fig. 2). Because each synoptic pattern/region transition is associated with

Table 1. Summary of synoptic pattern/region combinations depicted in Fig. 3 and illustrated by examples or case studies in this report that the forecaster may use to characterize the environment structure.

Pattern/ Region	Figure(s)	TC Name	Date(s) Beginning	YYMODDHH Ending	Track Figure	Remarks
S/EW						None during 1990-98
S/TE						
	4a	Georges	98091912	--	[6a]	[Characteristic tracks only]
	4a	TD09	98091912	--	[6a]	
	4b	Danielle	98082612	--	29	See also Figs. 20-21
	7d	TD05	97071800	--	[6a]	
	21a-b	Bonnie	98082012	98082300	20	S/TE →S/PF
	21 d-f	Danielle	98082600	98082800	20	See also Figs. 4b and 30
	26 a-b	Luis	95090212	95090412	25	S/TE →P/EF via ICIE
	26 d	Luis	95090512	--	25	P/EF → S/TE
	30 a-c	Danielle	98082900	98083100	29	S/TE → P/PF via RMT
	30c	Earl	98083100	98083112	29	S/TE → P/PF via RTF
	33 a-b	Jeanne	98092500	98092512	[6a]	S/TE → S/PF
S/PF						
	4b	Bonnie	98082612	--	20	
	4c	Humberto	98102800	--	[6b]	STIE
	21 c-e	Bonnie	98082312	98082700	20	S/PF → M/PF
	21 a-c	Charley	98082112	98082312	20	
	23 a-b	Sebastien	95102112	95102212	22	S/PF → S/EF
	33 c-d	Jeanne	98092600	98092612	[6b]	S/TE → S/PF
S/EF						
	4c	Iris	98082500	--	[6c]	STIW
	4d	Mitch	98102800	--	[6c]	
	23 c-d	Sebastien	95102312	98102412	[22]	VWS, MCG
P/PF						
	7a	Erika	97090800		[8b]	
	7b	Luis	95090800		25	ITIW
	7c	Roxanne	95100812		[8b]	ITIW
	26f	Luis	95090712		25	RMT
	30c	Danielle	98083100	98090112	29	RMT
	30d	Earl	98090100	98090300	29	RFT
P/EF						
	7c	Pablo	95010812		[8c]	ITIE
	26c	Luis	98090412	98090512	25	ITIE
P/EW						
	7d	Danny	97071800		[8d]	
U/PF						
	9a	Noel	95100100		[12a]	DCI
	9b	Isidore	96093000		12a	
U/EF						
	11	Nicole	98112400		[12b]	Also see Fig. 15d
M/PF	13a	Felix	95082112		[16a]	MCG
	13b	Lili	96102612		[16a]	
	21f	Bonnie	98082800		20	S/PF →M/PF
	30 e-f	Danielle	98090200	98090300	29	

Pattern/ Region	Figure(s)	TC Name	Date(s) Beginning	YYMODDHH Ending	Track Figure	Remarks
	30a	Bonnie	98082900		20	M/PF→ M/MW
	33 a-c	Ivan	98092600		32	
	33 c-d	Karl	98092600	98092612	32	
M/MW						
	15a	Grace	97101712		[16b]	
	15b	Ivan	98092612		32	
M/EF						
	15c	Gordon	94111912		[16c]	
	33a	Karl	98092500	98092512	32	M/EF→M/PF
M/ME						
	15d	Nicole	98112712		[16d]	Also see Fig. 11

a characteristic TC track change, it is important that the forecaster recognize that such a transition is (or will be) occurring.

A climatology of the recurring (at least four occurrences in nine years) environment structure transitions has been prepared (Fig. 19). Given knowledge of the present synoptic pattern/region, the forecaster should be aware that only certain transitions to other pattern/region combinations have been commonly observed. Considering the larger frequencies of occurrence for the S and M patterns, it is not surprising that many of the transitions involve these two patterns. That is, these transitions often involve a change from a westward track in the S pattern to a poleward and eastward track in the M pattern. However, a variety of transition mechanisms may be involved in these track changes. One key to successful track forecasting is thus to recognize the occurrence of the transition and correctly predict the timing of the track turn that will accompany that synoptic pattern/region transition. A complicating feature is that many of the transitions are two-way (see arrows in Fig. 19), which means that the transitional mechanism may only be short-lived. If that mechanism ceases to be present, or other external environment transitions counteract the steering flow change, the original synoptic pattern/region may be re-established. Since the general meteorological principle that forecasts during regime changes are less accurate than they are within the same regime also applies to TCs, the degree of difficulty of the track forecasts depends on the number of transitions that a TC experiences.

Various conceptual model of these transitional mechanisms have been presented in the text and specific examples of the evolution of the NOGAPS analyses during the transitions have been given in section 4. For convenience, the locations of these conceptual models and examples are summarized in Table 2 in the order they appear in Fig. 2. Specific examples are not given of the Advection (ADV) transitions related to the steering flow simply causing the TC to move from one region within the pattern to the next region along the arrows in Fig. 3, because this is so common. Similarly, Beta-effect Propagation (BEP) acts to some degree on every (dispersive) TC vortex. Only if the large size (strong outer winds) of the TC caused an anomalous poleward and westward component that facilitated a region transition would this BEP be listed as a transitional mechanism. In general, the Atlantic TCs tend to be relatively homogeneous in size compared to the western North Pacific TCs so that differences in BEP (Carr and Elsberry 1997) are not as important.

Table 2. Locator of figures illustrating the conceptual models and examples of Environment Effects and TC-Environment Transformations in the Transitional Mechanisms section of the Meteorological knowledge base in Fig. 2.

Transitional Mechanism	Conceptual Model Figure	pattern/region Changes	Example Figure	Remarks
Advection (ADV)	3 (arrows)	S/TE→S/PF S/PF→M/PF M/PF→M/MW		Plus similar transitions in other patterns involving advection without another transition mechanism
Midlatitude System Evolution (MSE)	14 a-b	S/TE→S/PF M/MW→M/PF		
	14 c-d	S/PF→S/EF	23	TC Sebastien
		M/MW→M/EF	33	TC Karl
Beta-effect Propagation (BEP)	27 a-b	S/TE→S/PF	--	Affects nearly all TCs to some degree
Ridge Modification by TC (RMT)	27 c-d	S/TE→P/PF	26	TC Luis
Reverse Trough Formation (RTF)	31 a-b	S/TE→P/PF (western TC) S/PF→P/PF (eastern TC)	30	TC Earl TC Danielle
Response to Vertical wind Shear (RVS)		S/PF→S/EF	23	TC Sebastien Can occur in other pattern/regions, especially M pattern
Direct Cyclone Interaction (DCI)	10	Cyclonic rotation within pattern	26a 9a	Karen -- Iris, Noel
Semi-direct Cyclone Interaction (SCI)	5 a-b	S/TE→S/PF (eastern) S/TE→S/EF	4c	Iris -- Humberto
Indirect Cyclone Interaction (ICI)	5 c-d	S/PF→S/TE (western) S/TE→S/EF (eastern)	26 7c 7c 26c	Luis (ICIW) Roxanne (ICIW) Pablo (ICIE) Luis (ICIE)

For the remainder of the transitional mechanisms in Table 2, an external influence other than advection or the beta-effect contribute to a transition. In the case of the RMT (RTF) transitions, the key circulation is the peripheral anticyclone(s) that forms to the southeast of the TC (two TCs), which introduces a poleward steering flow over the TC (both TCs). Response to vertical wind shear (RVS) is considered to be an external influence that removes the warm core aloft and decreases the intensity. Since the weaker TC is then advected by a lower-tropospheric steering flow rather than a mid-tropospheric steering flow, a track direction change may be introduced. In the case of the binary cyclone interactions (DCI, SCI, and ICI), the external influence is a second circulation in the proper location. In the Atlantic, this second cyclone could be a strong upper-tropospheric circulation that penetrates to the mid- or lower-troposphere and introduces a steering flow that affects the TC motion. The second cyclone may also be a vigorous midlatitude trough that sets up a Rossby wave dispersion into the tropics such that the motion of a (usually early or late season) TC is affected. Thus, the forecaster must take a larger view of the environment than just the immediate surroundings of the TC if the future environmental structure changes, and thus track changes, are to be forecast.

6. FUTURE WORK

The Meteorological knowledge base is just the first component of the Systematic Approach. As indicated in section 1.a, two other components are needed. First, a knowledge base of recurring TC track forecast errors is required. Carr and Elsberry (1999) have recently prepared conceptual models of cases in which the dynamical models have large (> 300 n mi) errors. They primarily examined the NOGAPS and Geophysical Fluid Dynamics Lab model version used by the U. S. Navy (labeled GFDN) track forecasts in the western North Pacific during 1997. Dunnavan *et al.* (2000) have extended the Carr and Elsberry NOGAPS and GFDN track error study for the western North Pacific to the 1998 season and also have summarized the track errors of the United Kingdom Meteorological Office (UKMO) and European Centre for Medium-range Weather Forecasts (ECMWF) global models for that basin during 1997-1998. Brown (2000) and Brown *et al.* (2000) have summarized the NOGAPS, UKMO, and ECMWF track errors for the Atlantic basin in terms of the Carr and Elsberry (1999) conceptual models. A similar study of large track errors by the NOGAPS, GFDN, UKMO, and ECMWF models in the Southern Hemisphere is in progress. Perhaps the most important conclusion from these studies is that the track errors arise because the dynamical model incorrectly predicts one of the transitional mechanisms (as in Fig. 2 for the Atlantic) that is known to cause track changes. By knowing these transitional mechanisms, and the likelihood that each model will tend to error in either an excessive or insufficient manner, the forecaster may be able to anticipate when the model track is likely to have a large error.

Peak *et al.* (1999, 2000) have been developing a Systematic Approach expert system for the western North Pacific under Office of Naval Research sponsorship. The expert system is essentially an information management tool that organizes the forecast procedure by displaying the analyses and forecasts in a logical sequence. Whereas the expert system has many pro-active features, the forecaster must consider the meteorological situation(s) and make decisions regarding the likely accuracy of the available objective guidance. A prototype module of the expert system that utilizes the Carr and Elsberry (1999) large-error conceptual models was tested in simulated real-time at the Naval Postgraduate School during the last half of the 1999 western North Pacific season. This test (Carr *et al.* 2000) demonstrated that it was possible to recognize when certain error sources were present (or not present) and thus improve on a simple numerical consensus of the model tracks. An improved module (called Systematic Approach Forecast Aid – SAFA) will be beta-tested at the JTWC during the 2000 season. Planning is in progress to adapt the SAFA to the Atlantic tropical cyclones.

The third component of the Systematic Approach is an implementing methodology or strategy for applying the Meteorological knowledge base and the Numerical Model and Objective Aid Traits knowledge base. As indicated above, work is in progress to develop the latter knowledge base. An Atlantic SAFA would be an important tool in implementing the methodology. The strategy for applying the Systematic Approach will evolve over several years of testing that must involve experienced forecasters who can set the acceptable parameter ranges, evaluate the uncertainties in the guidance, and apply acceptable risk management procedures.

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